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A DYNAMIC ANALOG FOR SYNCHRONOUS MACHINES

A THESIS

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ABSTRACT

Modern electrical power transmission systems with their associated generating equipment require that their planning engineers analyze both transient and steady state conditions on these systems. The steady state analysis can be performed easily on existing network calculators but the transient analysis is more difficult to complete. Power system engineers have long felt a need for some more convenient and less time-consuming method of study than is now available.

This thesis describes the steps necessary for the design, construction, and tests of an economical analog type of computer and servomechanism assembly to be used in conjunction with the network calculator at the Georgia Institute of Technology for the solution of transient stability studies. The basic idea of the analog computer unit follows a suggestion by E. W. Kimbark in a discussion of an A.I.E.E. conference paper in 1938.

The equation of motion of the individual machine to be represented on the network calculator is investigated and the usual assumptions are made in regard to speed, damping torques, saliency, voltage regulator, and governor actions. The resultant equation for the k-th machine is

$$\frac{d^2\theta_k}{dt^2} = \frac{1}{M}\,(P_{Ik} - P_{Ok}) \;.$$

In this equation, θ_k is the rotor angle; M is the inertia constant of the machine; P_{Ik} is the mechanical input power; and P_{Ok} is the developed electrical power. The computer to be used with the network calculator must solve this equation for θ_k and position the phase shifter accordingly.

In order to solve for θ_k, the computer must be supplied with the values of the input and output powers of the machine represented in the transient study. The output power is subtracted from the input power, and the difference is integrated twice with respect to time. The result of these operations will be proportional to the desired rotor angle of the machine and can be used to position the phase shifter. The basic advantage of Kimbark's suggestion over a special purpose computer is that the double integrator is the only additional equipment needed, since the existing network calculator will solve the equations of the electrical network.

Of all the types of integrators available, the induction watthour meter was picked as the best for this application, since a commercial two-element meter can perform the measurement of the powers, the subtraction, and the first of the two integrations. With modifications, as explained in the following paragraph, the meter will also perform the second integration.

The electromagnets of the watthour meter produce torques in the disc which are proportional to the power supplied. If the inertia of the disc is made proportional to the inertia constant of the machine to be represented, then the motion of the machine will be matched by the motion of the disc, providing that the damping and frictional torques in the watthour meter are eliminated. The effect of the frictional torque was eliminated by running the disc at a reference speed of 60 r.p.m. and by removing this speed by means of a synchro differential. The damping torque was greatly reduced by removing the damping magnets from the meter. The remaining damping torque due to the driving fluxes was cancelled by adding a driving torque proportional to the departure of disc speed from the reference speed. This driving torque was derived from the signal of a tachometer attached to the position servomechanism.

Because the watthour meter must not be loaded by extraneous torques, there must be a torque amplification between the disc shaft and the phase shifter. This amplification is obtained through a position servomechanism. The angle-sensing device is a synchro transmitter whose shaft and bearings support the watthour meter disc and the additional inertia. The signal from the synchro transmitter is fed to the synchro differential at which point the reference speed is removed. A synchro control transformer geared to the phase shifter shaft provides the error signal for the servo motor.

As expected, the servomechanism was found to have a small sustained oscillation due to the backlash in the gearing between the motor and the control transformer. This oscillation was eliminated by the addition of a tachometer feedback loop. The error in this servomechanism with a constant velocity input of 60 r.p.m. is 0.08 degrees.

The mechanical angle of the phase shifter shaft, as set by the computer-servomechanism combination, is the rotor position of the represented machine. This angle must correspond to the electrical angle of the phase shifter's output voltage. One way to accomplish this for all loading conditions is for the phase shifter to have zero internal impedance, which may be attained by cancelling the inductance with a series capacitor, and by cancelling the resistance with a negative resistance. The negative resistance is obtained from an amplifier which is connected in series with the phase shifter.

Following the detailed analytical design of the negative resistance amplifier, the servomechanism and the computer, three units were built, installed, adjusted, and tested. The tests were made on typical sample systems containing either one, two, or three machines and an infinite bus.

The results of the studies were recorded on a Brush direct-writing oscillograph, which recorded the output of a synchro control transformer whose stator windings were paralleled with the stator of the control transformer in the servo. Since the rotor of the auxiliary control transformer was blocked, the output was proportional to the sine of the watthour meter disc angle. Therefore, if the small error in the servomechanism is neglected, the phase shifter angle can be calculated.

The test studies were checked by the step-by-step method and a maximum error of 15.0 per cent was found. This percentage is taken with respect to the largest excursion of any machine in the test. While this error may be too large for a few particular studies, in a majority of studies it could be tolerated. Should the system be observed to be near the stability limit in the analog computer test, the study may be rerun by the more time-consuming step-by-step method.

Several refinements and modifications of design parameters are suggested for the over-all improvement of a commercial model. These modifications are not essential to the operation of the analog computer but will lead to ease of operation and control of the transient stability study.

The estimated cost of equipping a calculator is \$500 for each unit with an additional \$200 for voltage regulator control. In order to be economically feasible the analog computers must repay their cost by the operating time saved through their use. Their use in the more common steady state power flow problem would be to hold preset power outputs of the various generators which would materially reduce the time required to balance the system. The use of the analog computer would eliminate so much time consumed and drudgery in a transient stability study that an increase in the number of such studies should be expected.

CHAPTER I

INTRODUCTION

One of the major problems that confronts the electrical power system engineer is that of the transient stability of his particular system. Under any proposed operating condition the system should be able to absorb shocks such as switching surges or faults. Such disturbances cause the synchronous machines to oscillate, and the electrical network should be designed to prevent the generators from losing synchronism with one another. Two methods are available to the engineer with which he may evaluate the transient stability of the power system. These methods are mathematical analysis and analysis by analogy.

The mathematical approach is limited to systems that can be approximated by a two machine system because of the large amount of labor involved in the calculations when more than two machines are considered. By use of several methods[1,2], the stability of the two machine system can be evaluated. Punched-card or digital computers can be used for systems of more than two machines; however, their use has been limited, primarily because a study has to be completed before any data are available. On the other hand, the trend of a study on a

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[1]All superscripts refer to the bibliography.

network calculator type of computer can often be observed without completing the entire study and obvious errors corrected or necessary changes initiated immediately.

History of the Solution by Analogy.--A large number of analogy methods have been proposed, developed, and used. The principal one, as far as use is concerned, is to represent the electrical system on a network calculator, measure the power outputs of the various machines, and make a step-by-step determination of their rotor angles, plotting these data as "swing curves"[3]. This method has the disadvantage of being extremely time-consuming since it may take several hours of computer time to determine the events occurring in one second of time in the actual system. This incremental method is also subject to errors due to the finite time interval used in the calculations. However, this error can be made small by use of small time increments.

Boast and Rector[4] developed a method of representing the mechanical constants of the rotating machines by resistances and inductances in an all electrical analogy of the entire system. This requires d-c amplifiers and photoformers as additional equipment and a preliminary study on the network calculator to determine the transfer and driving point impedances of the network. Robert[5] proposes the use of miniature three-phase machines with interchangeable rotors driven by d-c motors. Feedback amplifiers would be used to match the actual system and its time constants. Here the disadvantage lies in the cost and size of the equipment and the control of prime-mover speed and generator voltage during the set up period. Concordia[6] has used the mechanical differential analyzer to determine the effect on stability of governor and voltage regulator actions. This use is limited by the inability of a moderate size differential analyzer to solve the equations of the electrical network in the general problem.

The disadvantages of the analogies already mentioned are largely overcome by Kimbark's[7] proposal that a computer be coupled directly to the network calculator to position the phase shifters automatically in accord with the equations of motion of the rotor of the actual machine. The advantages of the proposal are twofold: the existing network calculators are admirably suited to the solution of the network equations and the only additional equipment necessary is the computer to solve the equation of motion. In addition, a control of this type could be used very advantageously in steady-state load-flow studies to maintain the power output constant at a preset value. This thesis is based on a computer of this general nature.

A computer following Kimbark's suggestion was developed by Cloues and Vance[8] with additional modifications and improvements by Heller[9]. The latter used two watthour meters as integrators. Photoelectric pickups were used to supply the error signal to the position servomechanism that controlled the phase shifters. Heller estimated that to completely equip a network calculator with these units would increase the cost about twenty per cent. Van Ness[10], Shen and Lisser[11] have devised similar computers for those network calculators that use amplifiers and phase shift networks as generators rather than the more common type which use three-phase induction regulators and phase shifters as power sources. The technical disadvantages of all these units that were based on Kimbark's suggestion are that they are one of a kind and have only been tested on systems that can be represented by one machine and an infinite bus. Thus, there is still a question of accuracy and practicability in the use of these units in a multi-machine system.

Mathematical Introduction.--The primary results necessary from a study of the transient stability of a system are the swing curves or the excursions of the rotor angles of the various machines on the system. Certain simplifying assumptions are usually made for the purpose of facilitating the solution. These assumptions are:

1. The speed of the machine remains practically constant during the test period.
2. Damping torques are negligible.
3. The machine is represented by the direct axis transient reactance in series with a constant electromotive force whose electrical phase angle is proportional to the mechanical angle of the rotor. This angle is measured with respect to a synchronously rotating reference.
4. The power input is constant during the test period.

5. The electrical power measured on the network calculator corresponds to the output power of the actual machine.

These assumptions will not be justified herein, but a discussion of their bases will lead to a better understanding of the equations that follow.

Assumption No. 1 is made on the basis that during the swings of the rotor angles the percentage change in speed is small until after synchronism is lost. Thus, the question of whether or not the system is stable has been answered before the velocity departs appreciably from synchronous speed.

Damping torques arise primarily from damper windings and thus depend on a departure of velocity from synchronous speed and are neglected for the same reason as No. 1 above.

Assumption No. 3 is not entirely correct, especially for salient pole machines. However, this assumption greatly simplifies the solution, usually without serious error, and in dubious cases the more tedious and time-consuming methods can be used. This assumption also neglects the action of any voltage regulating equipment on the machines, which will usually give pessimistic answers.

The assumption that the power input is constant is made on the basis that the governor will not have time to act and thus change the input to the prime mover.

Assumption No. 5 really involves two ideas. The power measured on the calculator will be almost steady-state power set by the network impedances, the internal electromotive forces, and their relative phase angles. In the power system sudden changes are taking place giving rise to a number of transient effects that are not included on the calculator. This assumption is made on the basis that these transients die out very rapidly compared to the period of the system oscillation and therefore make a negligible contribution to the swing.

The equation of motion of the rotor on the k-th machine in a system to be studied is given by

$$J_k \frac{d^2\alpha_k}{dt^2} + T_{Dk} = T_{Ik} - T_{Ok} . \qquad (1)$$

J_k is the polar moment of inertia of the alternator and prime mover in slug-feet squared,

α_k is the mechanical rotor angle of the alternator in radians with respect to an arbitrary synchronously rotating reference,

T_{Dk} is the damping torque of the alternator and prime mover in pound-feet,

T_{Ik} is the input torque to the alternator from the prime mover in pound-feet, and

T_{Ok} is the electrical output torque delivered across the air gap of the alternator in pound-feet.

This equation can be simplified considerably by making use of assumptions Nos. 1 and 2. When Eq. (1) is multiplied by synchronous speed, n_{sk}, and T_{Dk} is neglected, the result is

$$J_k \, n_{sk} \frac{d^2\alpha_k}{dt^2} = n_{sk} \, T_{Ik} - n_{sk} \, T_{Ok} . \qquad (2)$$

However,

$$\frac{2\pi \times 746}{33} \times 10^{-6} \, n_{sk} \, T_k = P_k \, , \tag{3}$$

$$\frac{d^2\alpha_k}{dt^2} = \frac{\pi}{180} \frac{2}{p_k} \frac{d^2\theta_k}{dt^2} \, , \tag{4}$$

$$J_k = \frac{(WR^2)_k}{32.2} \, , \tag{5}$$

and

$$n_{sk} = \frac{120f}{p_k} \tag{6}$$

where P_k is the power in kilowatts associated with the torque T_k,

θ_k is the electrical phase angle in degrees of the alternator internal voltage with respect to an arbitrary reference,

$(WR^2)_k$ is the polar moment of inertia in pound-feet squared,

n_{sk} is the synchronous speed of the alternator in r.p.m.,

f is the normal output frequency, and

p_k is the number of poles of the alternator. Therefore, the combination of Eqs. (2), (3), (4), (5), and (6) gives

$$1.283 \times 10^{-9} \frac{(WR^2)_k \, n_{sk}^2}{f} \frac{d^2\theta_k}{dt^2} = P_{Ik} - P_{Ok} \, , \tag{7}$$

Let

$$M_k = 1.283 \times 10^{-9} \frac{(WR^2)_k \, n_{sk}^2}{f} \, . \tag{8}$$

The units for M are kilojoule-seconds per degree. Now Eq. (8)

is substituted into Eq. (7) which gives:

$$\frac{d^2\theta_k}{dt^2} = \frac{1}{M} (P_{Ik} - P_{Ok}) \; . \tag{9}$$

This is the equation that the k-th computer must solve and combine with the initial conditions of the k-th alternator (θ_k and $\frac{d\theta_k}{dt}$ at $t = 0$).

The computer must be supplied with a constant reference, P_{Ik}; subtract from it the electrical power developed in the generator and integrate this result twice with respect to time. The position servo must then position the phase shifter which represents the alternator to this new rotor angle, also taking into account the scaling factor $\frac{1}{M}$.

It should be noted that M covers a wide range of values in different machines and that the literature uses another value, H, defined as

$$H = \frac{180 \; M \; f}{G} \tag{10}$$

where G is the kva rating of the machine. For a particular class of machines H is more nearly constant than M.

Purpose of This Thesis.--The primary disadvantage of the previously-described computers following Kimbark's suggestions is that they have not been tested on a system larger than one machine and an infinite bus. Thus, the tests of accuracy and practicability are inconclusive when an attempt to apply them to a large system is made. In addition, the economics of network calculator operation dictate that the unit cost of a computer be small.

The purpose of the research was to design an economical computer to be applied to the calculator at the Georgia Institute of Technology, to construct three such units, and to conduct suitable tests of their accuracy and ease of operation. This thesis describes these steps.

CHAPTER II

DESIGN OF THE COMPUTER AND POSITION SERVOMECHANISM

A block diagram of the computer, servomechanism, and phase shifter to represent the dynamic analog of one synchronous machine on the network calculator is shown in Fig. 1. In this ideal case the transfer function of the computer would be found from the solution of Eq. (9);

$$\theta_k = \theta_k(0) + \frac{d\theta_k}{dt}(0)t + \frac{1}{M}\int_0^t\int_0^t (P_{Ik} - P_{Ok})(dt)^2 , \quad (11)$$

where θ_k (0) is the initial value of the phase angle and $\frac{d\theta_k}{dt}$ (0) is the initial velocity of the k-th machine. Thus, the computer will consist of a differencing and a double integrating device.

The ideal position servo will have a transfer function of unity, and the ideal phase shifter will have a constant output voltage whose electrical phase angle exactly duplicates the mechanical phase angle input from the position servo. The following sections deal with the realizability of these ideal components.

<u>The Phase Shifter</u>.--The Georgia Tech Network Calculator uses a 440 c.p.s. generator to supply the power to the voltage regulators and phase shifters which represent the system machines. Base voltage on this calculator is 100 volts and base current

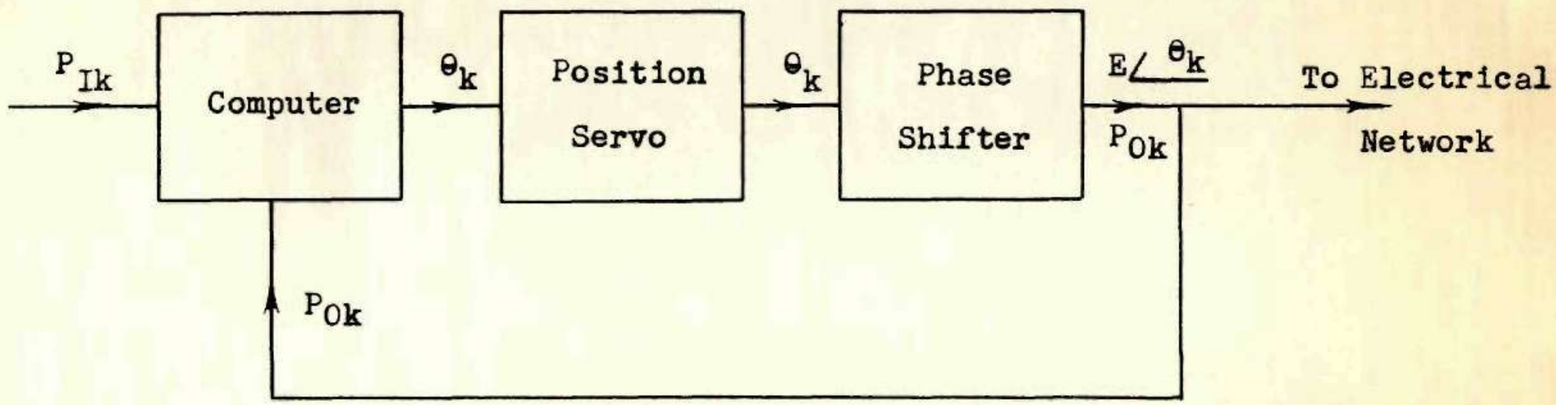


Figure 1

Block Diagram of One Unit

is 1.0 ampere. However, the generators are metered to supply a maximum of 4.0 amperes. It was decided to design the computer and auxiliary equipment for a maximum of 4.0 amperes.

The internal impedance of the phase shifter-voltage regulator combination is approximately three ohms resistance with the inductive reactive component cancelled by appropriate series capacitors. This internal resistance would cause the output voltage of the phase shifter to vary twelve volts from no load to four amperes output at unity power factor, and would cause the electrical phase angle to depart appreciably from the mechanical angle under loaded conditions at other than unity power factor. Either of these conditions would render the existing phase shifter unsuitable for this investigation.

An automatic voltage regulator would furnish the constant output voltage required but would not make the mechanical and electrical phase angles agree except under particular loading conditions. However, both voltage regulation and phase angle control could be accomplished by cancelling the internal resistance of the phase shifter. The requirement would be a negative three ohm, forty-eight watt resistor.

Ginzton[12] describes a "series" type of negative resistance whose characteristics are stabilized by negative feedback. This type was used with minor modifications.

If an amplifier, with its gain stabilized by negative feedback, has external connections as shown in Fig. 2, then the following statements are true. With the switch S_1 in position "a" and a voltage, V_s, between terminals 1 and 3, circulating a current, I_s, through R_1, the amplifier will supply power to the load, R_L. The load current will be

$$I_L = \frac{A_v V_s}{R_L} \; . \tag{12}$$

Now let

$$R_L = A_v R_1 \; . \tag{13}$$

Eq. (13) substituted into (12) yields:

$$I_L = \frac{A_v V_s}{A_v R_1} = \frac{V_s}{R_1} = I_s \; . \tag{14}$$

Under these conditions the position of switch S_1 will have no effect on the amplifier, providing a voltage, V_o, is established at the value given by Eq. (15).

$$V_o = V_s - A_v V_s = V_s\,(1 - A_v) \; . \tag{15}$$

The impedance looking into terminals 1-2, with the switch in position "b", is

$$Z_o = \frac{V_o}{I_s} = \frac{V_s(1 - A_v)}{I_s} = R_1(1 - A_v) \tag{16}$$

Thus, if A_v is greater than 1.0 then Z_o is a negative resistance but, at the same time, the amplifier sees a load of R_L across its output terminals.

The resistance needed is minus three ohms. If a convenient value of $R_1 = 0.3$ ohm is taken, then $A_v = 11.0$ and

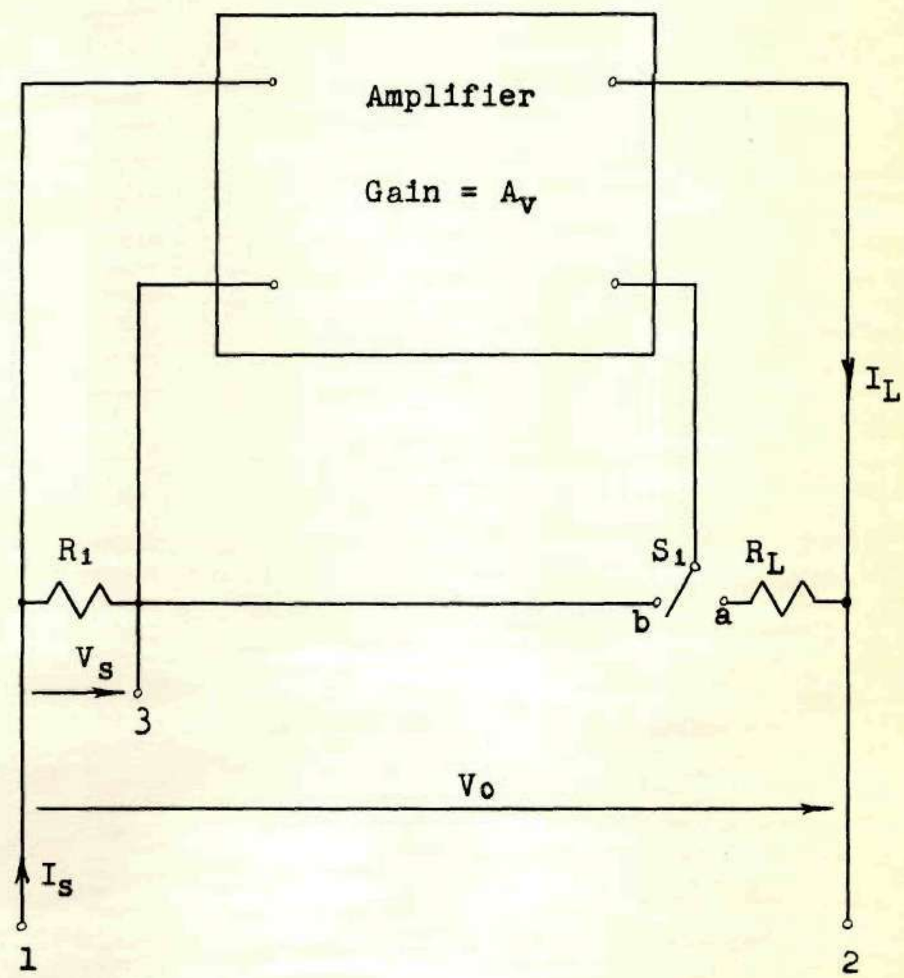


Figure 2

Series Type of Negative Resistance

R_L = 3.3 ohms. The amplifier necessary to complete the negative resistance should have a gain of 11.0 when supplying a 3.3 ohm load and should have a maximum power output of at least 52.8 watts.

The design of the amplifier to satisfy these requirements is given in Appendix I and the circuit diagram of the completed design is shown in Fig. 3.

The negative resistance was tested with the phase shifter and showed a voltage regulation of 0.5 per cent at four amperes output. This regulation was principally due to a small amount of reactance that was not cancelled by the series capacitor.

<u>The Computer</u>.--The computer to solve Eq. (11) could assume many forms. The heart of any of these would be the integrating element or elements. Integrating elements available are mechanical integrators[13], electronic integrators[14], velocity servomechanisms[15], digital methods and the watthour meter[16].

The mechanical integrator is eliminated as a possibility in this investigation because of its initial cost and space consumption.

The accuracy of electronic integrators depends on an RC time constant and the gain of an amplifier. It would be desirable to have a time scale expansion in the stability study of at least 300 to 1. Thus, a study of one second of system time would require accurate integration periods of five minutes. This is an appreciably longer time than present low-cost

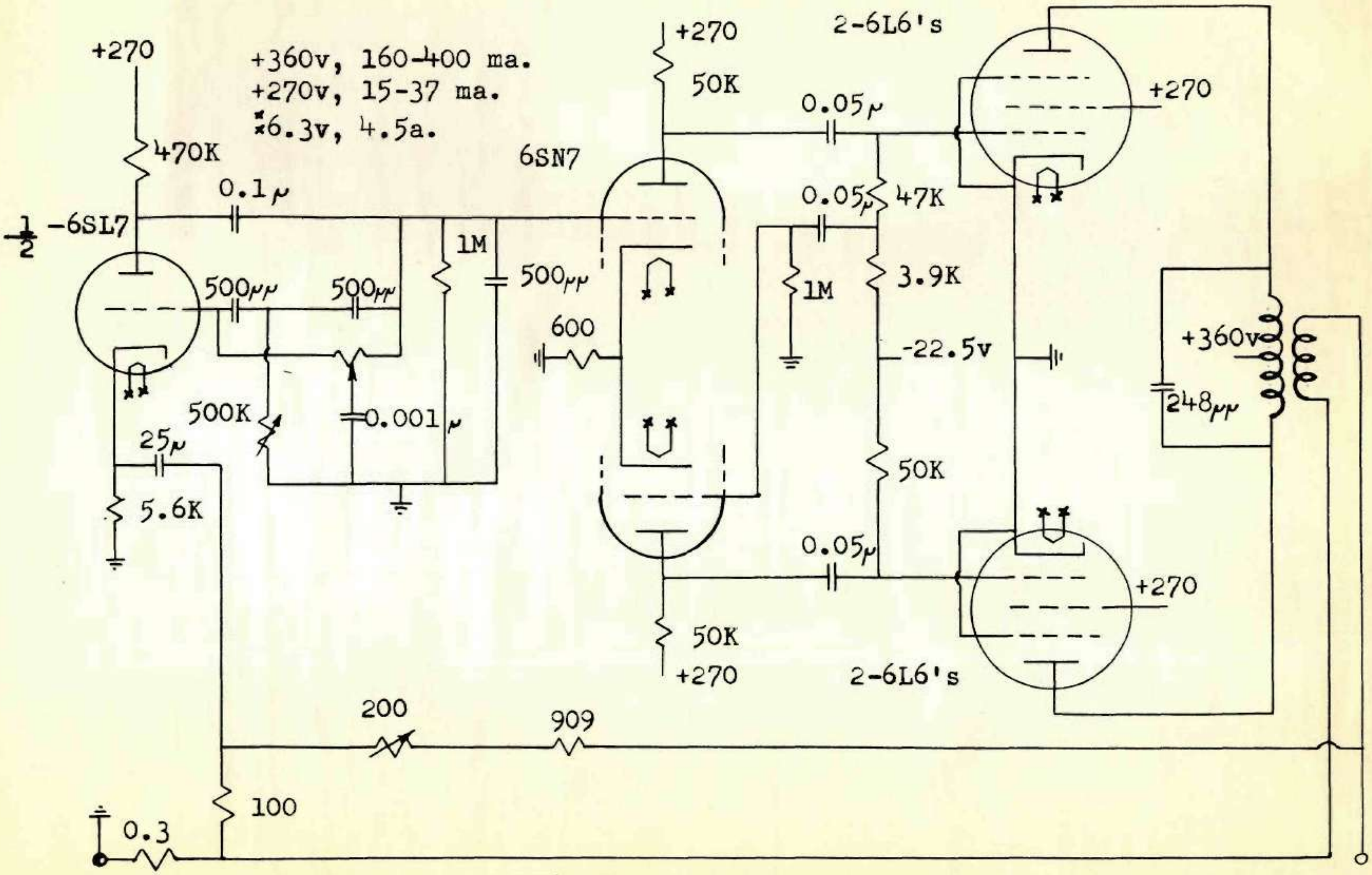


Figure 3
Circuit Diagram of the Negative Resistance

electronic integrators will integrate satisfactorily.

A velocity servomechanism could be used; however, any drift in it would be cumulative and such a servo that was practically drift free would be uneconomical. Digital methods of integration would involve complex and costly analog-to-digital-to-analog conversions.

The watthour meter offers the best possibilities for this application. It is an inexpensive yet accurate integrator of electric power. Thus, the combined function of power measurement, difference and integration can be performed by a commercial model of a two element meter. Other torques, such as caused by the negative sequence currents, could be combined with P_o and P_I if desired. This would require more elements on the same shaft.

There are two possibilities in the use of a watthour meter as the integrating element. The first is to supply a commercial two element meter with powers P_I and P_o. Obtain the integral from the revolutions of the disc and use these revolutions in conjunction with a position servo to drive a variac which will then give an output voltage proportional to the integral and with a phase position denoting the sign. This voltage could then be integrated by means of another watthour meter supplied with constant current, and the follow-up servo would then position the phase shifter.

The second possibility is to remove the damping magnets from the watthour meter and add enough inertia to the disc so that the equation of motion, Eq. (9), will be satisfied by the motion of the disc. The first requires two watthour meters and two position servos, while the second requires only one of each. The scaling factor, $\frac{1}{M}$, in either case can be secured by simple electrical means, such as current transformers to supply the watthour meter with $\frac{P_o}{M}$. This second method was adopted because of the improved economics afforded by the use of only one watthour meter and position servo.

There are certain inherent disadvantages in the use of the increased inertia system. The first disadvantage is due to the increased time scale which is necessary to complete the switching manually. If the time scale is expanded by a ratio of 900 to 1 and the actual system takes one minute to completely settle down after a disturbance, then on the analog it will take 900 minutes or 15 hours to reach a steady state operating condition after each stability study. Thus, a system of damping must be provided in order to reach steady state conditions quickly after each study is run.

The second disadvantage is due to the large amount of inertia needed. This additional weight would overload the bearings in a watthour meter and thus either rupture them or increase the friction by a large percentage. Also since P_o can be either greater or less than P_I the watthour meter must be friction compensated in two directions instead of just one. This latter defect can be remedied by establishing reference speed at some level other than zero and by removing this reference in the servo system by some differential device. Thus, the watthour meter will run unidirectionally while the output with the reference removed will run bidirectionally.

The desired equation of motion of the phase shifter shaft, including the time scale change, can be found by letting

$$T = \mu\ t \tag{17}$$

where T is the computer time and t is the actual system time. Thus,

$$\frac{d^2\theta}{dT^2} = \frac{1}{\mu^2}\frac{d^2\theta}{dt^2} . \tag{18}$$

Eq. (18) is substituted into Eq. (9).

$$\mu^2 \frac{d^2\theta}{dT^2} = \frac{1}{M}\left(P_{Ik} - P_{Ok}\right) . \tag{19}$$

The system is set up on the network calculator on a per-unit basis and in order to so arrange Eq. (19) it is multiplied and divided by base kva.

$$\frac{d^2\theta}{dT^2} = \frac{\text{Base kva}}{\mu^2 M} \quad \frac{P_I - P_O}{\text{Base kva}} . \tag{20}$$

The equation of motion of the disc in a two element watthour meter is given by

$$J\frac{d^2\beta}{dT^2} + D_p\frac{d\beta}{dT} + F = K_p(P_1 - P_2) . \tag{21}$$

In this expression:

β is the disc angle in radians,

J is the disc inertia in slug-feet squared,

D_p is the damping coefficient due to the driving fluxes[17],

F is the frictional torque opposing rotation,

P_1 is the input power to electromagnet No. 1 in watts,

P_2 is the input power to electromagnet No. 2 in watts,

and K_p is the torque to power ratio of the watthour meter in pound feet per watt.

If the reference speed on the disc is set at ω radians per second, then

$$\beta = \omega T + \delta \tag{22}$$

where δ is the disc angle with respect to the rotating reference. Eq. (21) then becomes

$$J \frac{d^2\delta}{dT^2} + D_p \frac{d\delta}{dT} + (D_p\omega + F) = K_pP_1 - K_pP_2 \; . \tag{23}$$

Preliminary adjustment of P_1 must be just enough to cancel the term in the parentheses.

In order to match the motion of the disc to the desired motion, the damping term in Eq. (21) must be made at least as negligible as the corresponding term in Eq. (1). This can be accomplished by keeping the driving fluxes as small as possible and increasing the moment of inertia, J. However, J is set by the constants of the watthour meter, the machine to be represented, the time expansion of the study, and the kva base chosen for the study. In most cases there is little or no room for change in these constants. Thus, the damping or velocity torque must be compensated in some manner other than changing the moment of inertia.

The position servo on the phase shifter must follow δ closely, and thus a tachometer attached to the servomechanism motor will give a voltage proportional to $\frac{d\delta}{dT}$. This voltage may be amplified and fed to the watthour meter No. 1 coil. An additional term is then added to the power expression in Eq. (23). This input can be adjusted to cancel the damping term. By reversing this voltage additional damping will be present to aid the system in its return to steady state conditions. Thus, the previously mentioned disadvantage of a long time to reach steady state is largely overcome.

The design of the amplifier to supply the watthour meter electromagnet No. 1 is given in Appendix II.

The initial adjustment of P_1 and the tachometer feedback term will leave Eq. (23) in this form:

$$J \frac{d^2\delta}{dT^2} = K_p(P_{11} - P_2) \tag{24}$$

where P_{11} is the excess power to element No. 1 above that necessary to cancel the damping and constant torque terms. In order to match Eq. (24) to Eq. (20), the dimensions must be the same. The following equations are needed.

$$\frac{57.3\delta}{N_g} = \theta \ , \tag{25}$$

where N_g is the gear ratio between the servo motor and the phase shifter shaft.

$$\frac{P_0}{\text{Base kva}} = \text{per unit power} = \frac{P_a}{100} \; . \tag{26}$$

If Eqs. (25) and (26) are substituted into Eq. (24) and solved with Eq. (20) for J, the resultant equation is

$$J = \frac{5730\, K_p\, \mu^2\, M}{N_g \text{ Base kva}} \; . \tag{27}$$

A wide range in the values of M will be encountered in the same system study and therefore some simple means of reflecting these values in the computer is necessary. Since a change in inertia would require that a large number of flywheels were available to meet any possible value of M, a combination of mechanical and electrical effects is used. With a fixed inertia a certain M can be duplicated by adjusting K_p. This constant can be varied by using current or potential transformers to supply the watthour meter element with a power proportional to P_0.

The Position Servomechanism.--Because the watthour meter element must not have any extraneous torques acting on it, there must be a torque amplification between the revolving disc and the phase shifter on the network calculator.

A photoelectric pickup, as shown by Berry[18], was considered because of its zero load on the primary element but was eliminated because of the additional equipment needed and because of the fact that the computer would have to be mounted near the phase shifter. The space near the phase shifter shaft is fixed by the present construction of the network calculator and is quite limited. Physical dimensions are given in Appendix III.

Pure frictional load on the computer can be balanced out by an increase in the P_1 driving term in Eq. (23) as mentioned previously. Therefore, a small synchro transmitter can be used as the angle-measuring device on the watthour meter disc. A synchro differential running at reference speed can remove the reference velocity and then a synchro control transformer will give the error signal necessary for the position servomechanism. The watthour meter disc and additional inertia can be mounted directly on the synchro transmitter, using its bearings to support the additional weight. This construction eliminates the need to overload the precision bearings in the watthour meter.

It was found in the design of the servo that due to the backlash in the gears between the servo motor and the phase shifter a small oscillation was maintained. This was eliminated by proper feedback of the tachometer output.

The mechanical and electrical design of the servomechanism and its construction is covered in detail in Appendix III.

The block diagram of an entire unit to represent one synchronous machine on a power system is shown in Fig. 4.

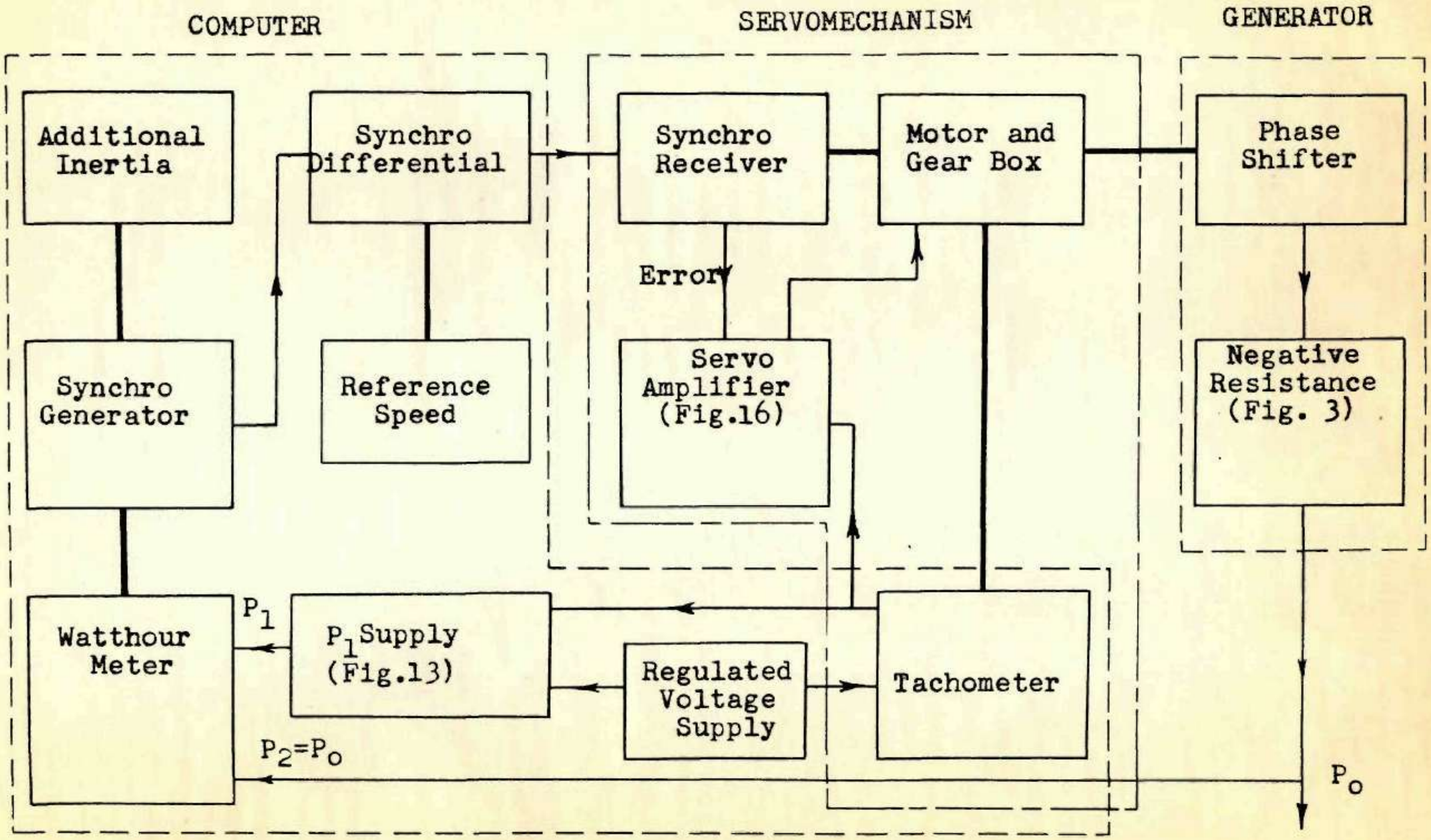


Figure 4
Detailed Block Diagram of One Unit With Major Subdivisions Illustrated

Mechanical linkages are indicated by heavy lines. Necessary regulated voltage sources are indicated because they form a part of the measuring process of the computer. It can be seen that the tachometer is used as a part of the computer and also in the position servomechanism. The principal subdivisions are separated by dotted lines.

CHAPTER III

TESTS ON THE UNITS

After the detailed design of the computers and servos was completed, three units were constructed and installed. These units are shown in Fig. 5. The numbered items are: 1 - the constant voltage transformer, 2 - the servo motor amplifiers, 3 - the reference speed synchro differential unit, 4 - the negative resistance amplifiers, 5 - the computer units, and 6 - the power supplies. The servo motor and gear box assemblies are not shown because they are mounted directly on the phase shifter behind the front panel of the calculator.

Typical sample problems were conducted after the preliminary adjustments had been made. To check the accuracy of the problem run, necessary measurements on the sample problem were made. These included the steady state starting conditions and the swing curves of the various generators.

Measurements.--In order to obtain the swing curves, it was necessary to record the phase shifter angle. In a commercial model it would be desirable to accomplish this by means of a potentiometer coupled directly to the shaft and supplied with a constant d-c voltage. The output of the potentiometer would then be proportional to the shaft angle. The method used, however, was much simpler in construction but more

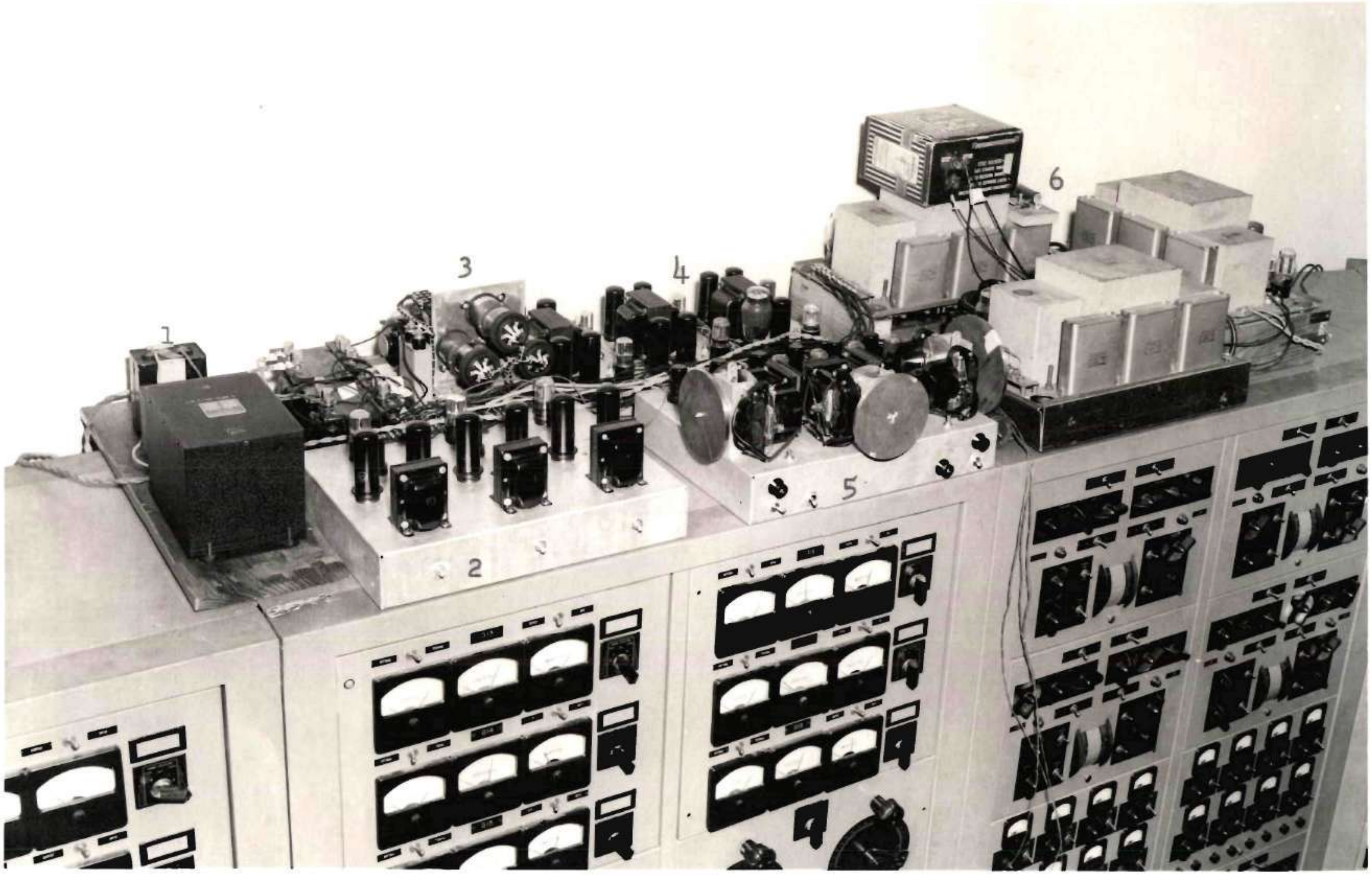


Figure 5
A View of the Installation on the Network Calculator

difficult in interpretation. An additional synchro control transformer with fixed rotor position was connected to the synchro differential and the error signal was recorded by means of a Brush recorder. Fig. 6 shows the installation complete with the Brush recorders in place. The recorded error signal is proportional to the sine of the angular displacement between the watthour meter disc and the reference, and thus gives an indication of the total angle, δ, between the two. The total angle of the phase shifter can then be obtained by the summation of the rotation recorded divided by the gear ratio plus the original steady state angle. Samples of these data are shown in Fig. 7. The (a) part shows a section of the record from the beginning of a study. Section (b) shows a period in which a reversal in direction of rotation takes place. Both sections show the angle of the watthour meter as calculated at selected points. The chart is run slowly so that the envelope of the 60-cycle carrier is clearly indicated.

The phase angles resulting from the calculations made on the charts will actually be the phase angle of the watthour meter rather than that of the phase shifter. The difference will be the error of the servomechanism. In Appendix III this maximum error is found to be approximately 0.08 degrees, and thus the angle calculated from the synchro transformer output will be within the limits of the accuracy desired.

Sample Problems.--Three types of sample problems were set up and tested. These were one, two, and three machine problems -

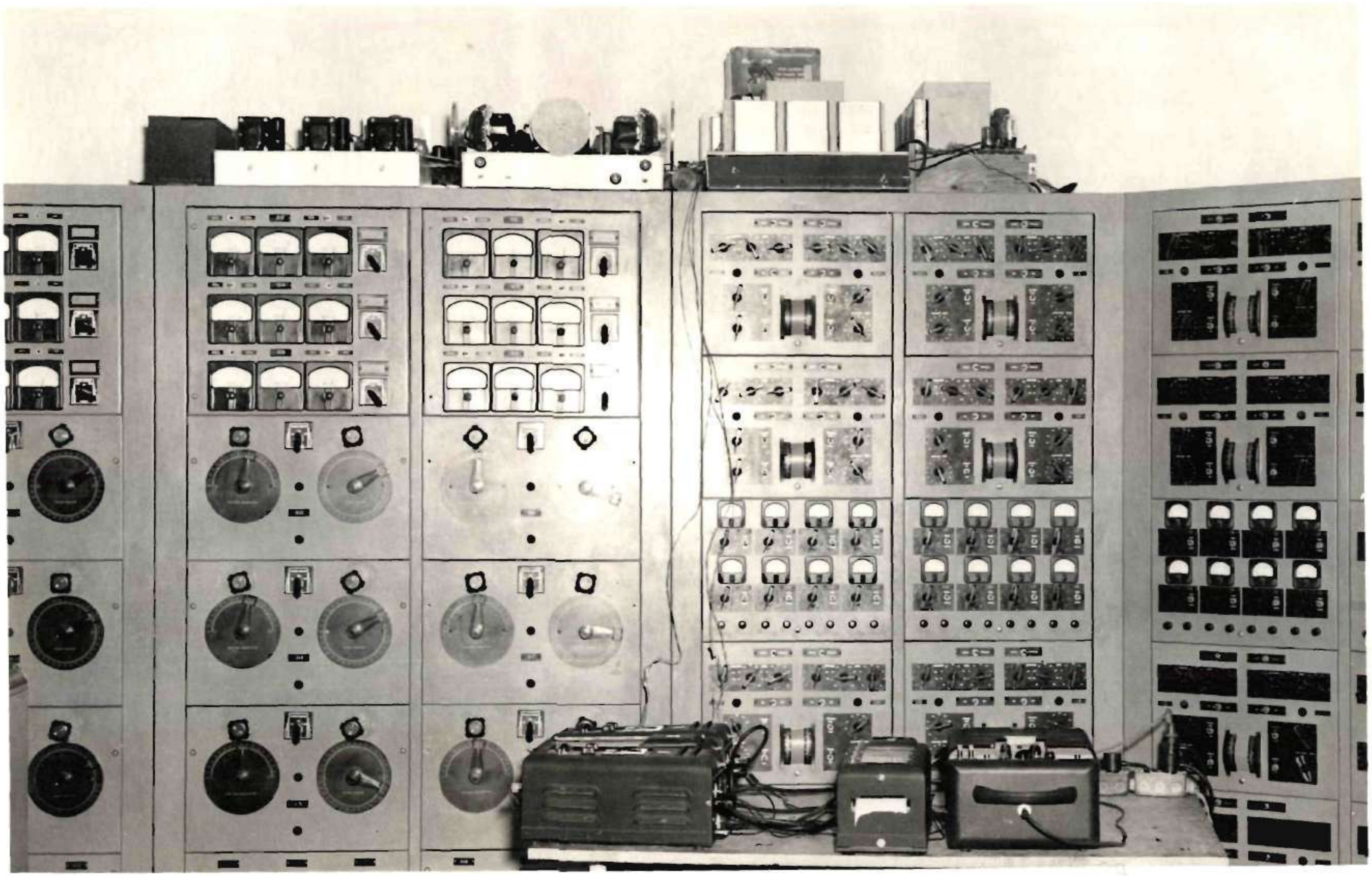


Figure 6
Another View of the Installation Showing the Brush Recorders

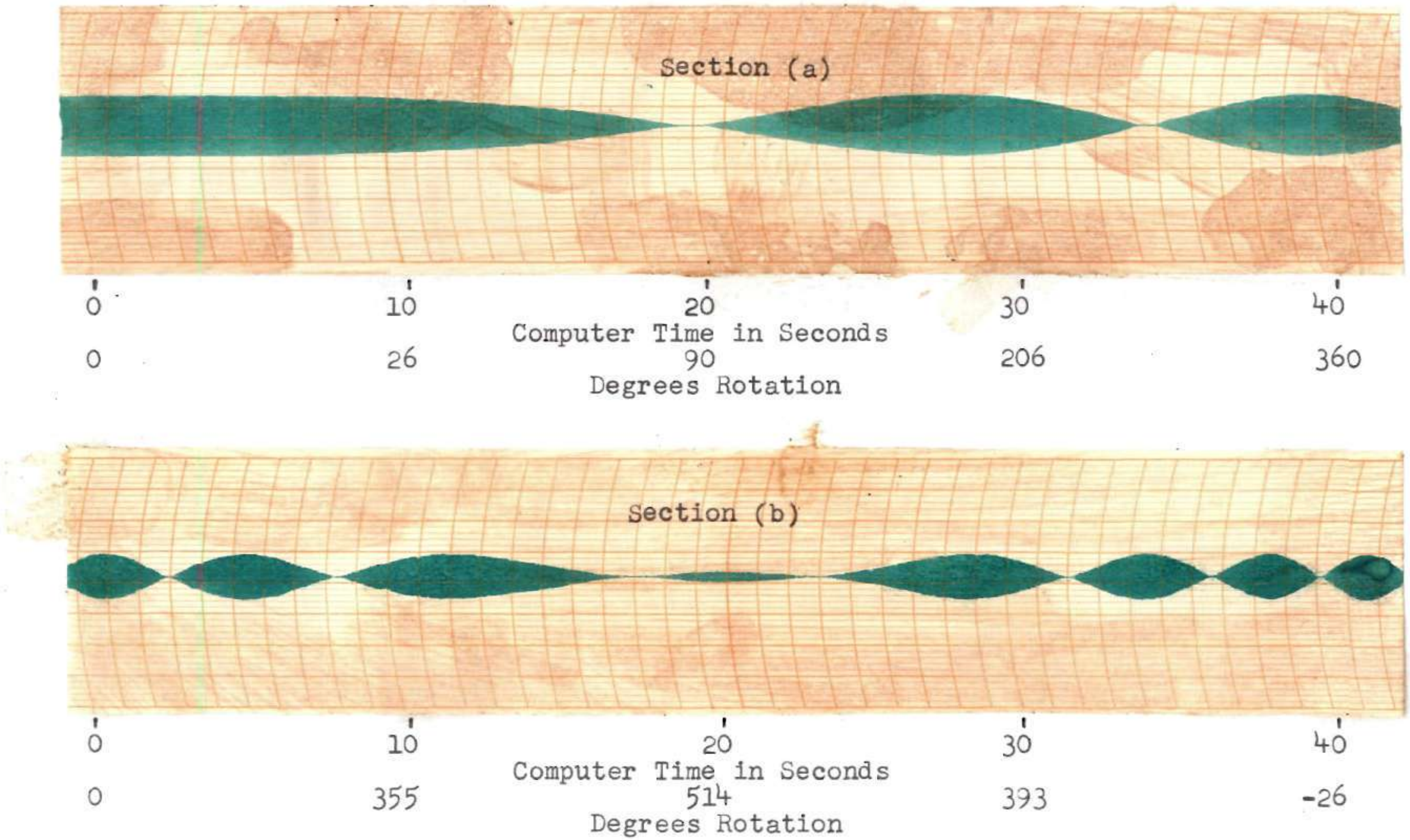


Figure 7

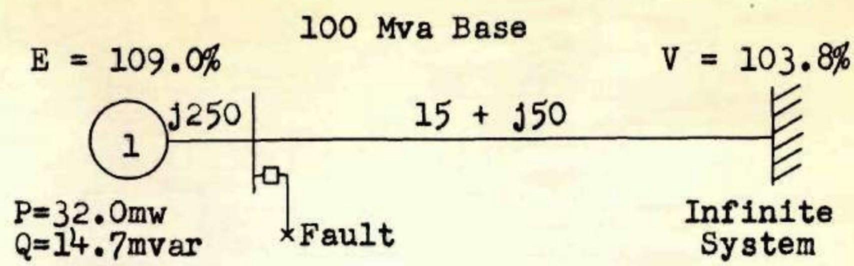
Typical Data Record of a Swing Curve

each system also containing an infinite bus. Each of the tests was checked by means of the conventional step-by-step procedure. A short time interval was used in order to keep the errors due to finite time difference small.

Representative samples are shown in Figs. (8), (9), and (10). The schematic shows the power system and its constants, and the swing curves show the results of the computer study (solid line) and points on the step-by-step check. Two time scales are given: system time and computer time.

From these curves it is seen that the maximum error is 15 per cent compared to the largest excursion of any machine. There seems to be a tendency for this error to increase as the study progresses. This error is within acceptable limits for a majority of stability studies. The limitation on study time span is acceptable because the assumptions made on most stability studies limit the time span to one second of system time. After this time the validity of the assumptions is very questionable. The error of the computer can be tolerated in many studies because it will still be possible to determine if the system is near the stability limit and, if it is, to rerun the study by the step-by-step method and, in addition, take into account secondary effects not covered in the basic assumptions.

Practical Problems Encountered.--There were several problems encountered in the construction and operation of the computer units.



Machine No. 1, H = 5, Mva Rating = 50

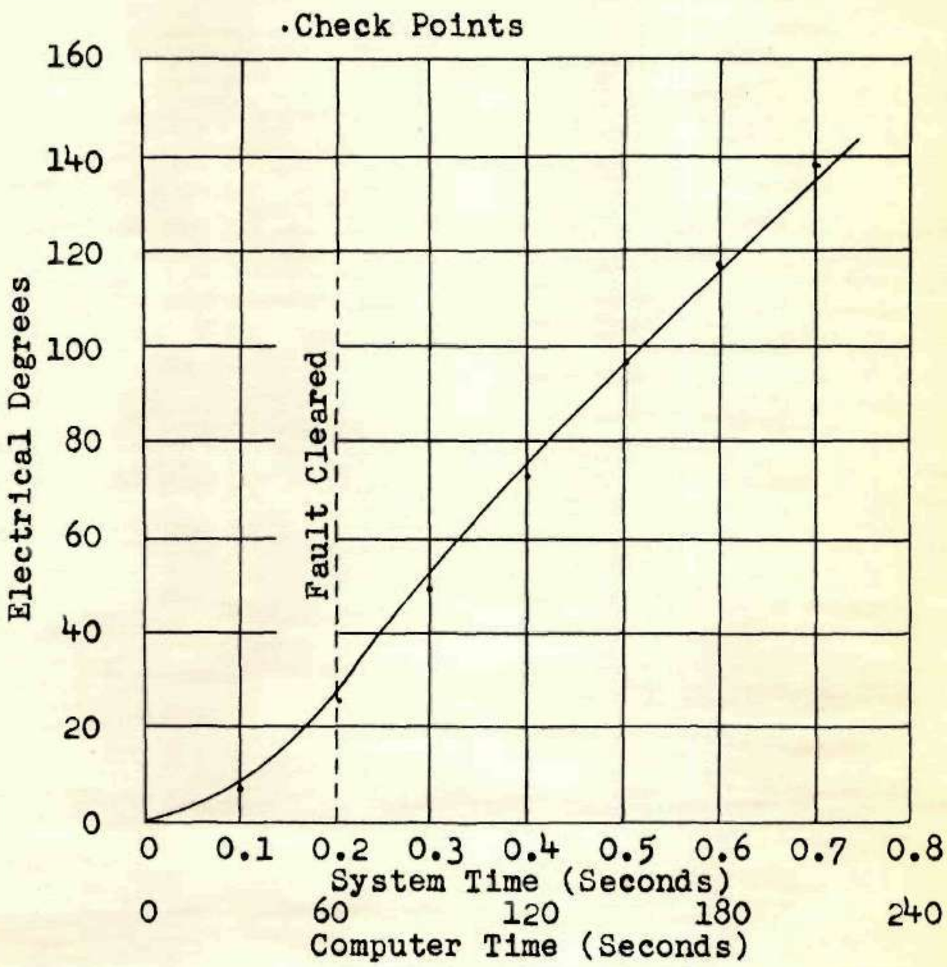
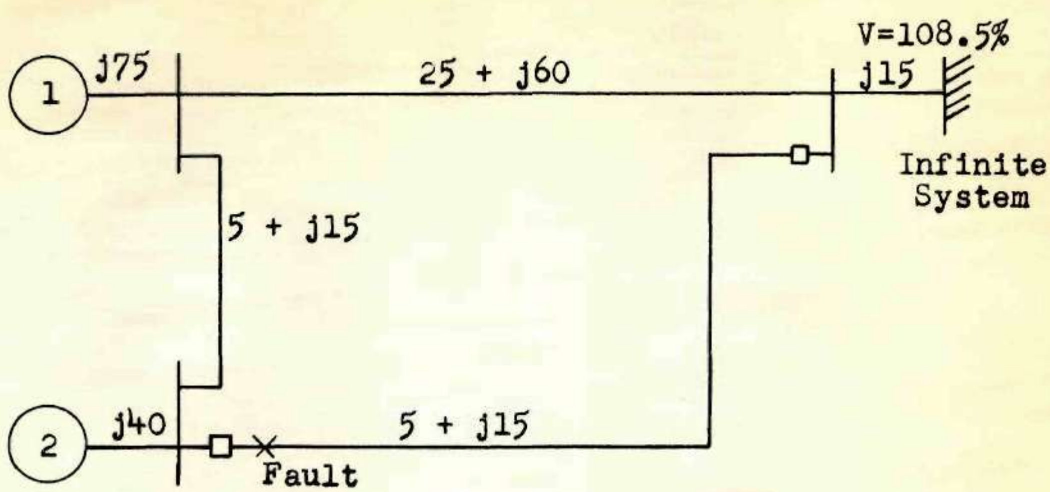


Figure 8

Single Machine and Infinite Bus System

100 Mva Base



Machine No.	H	Mva Rating	P mw	Q mvar	E%
1	6.13	35.0	32.5	0	109.5
2	8.68	100.0	57.0	-18.0	109.0

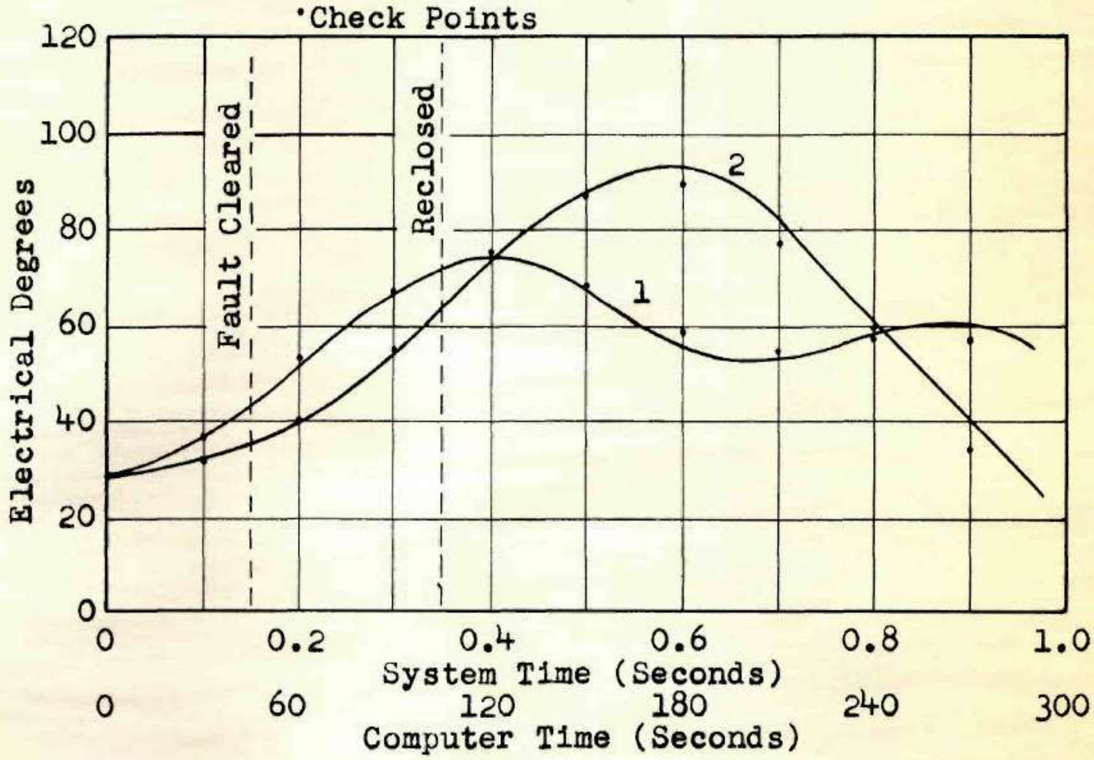
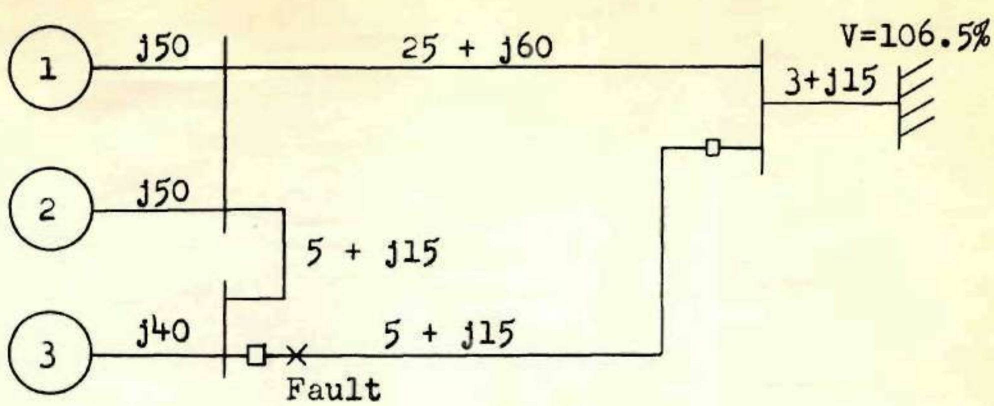


Figure 9

Two Machine Test System

100 Mva Base



Machine No.	H	Mva Rating	Pmw	Qmvar	E%
1	5.0	50	32.5	0.0	109.8
2	6.13	35	29.5	1.8	109.8
3	8.68	100	46.0	-13.0	107.5

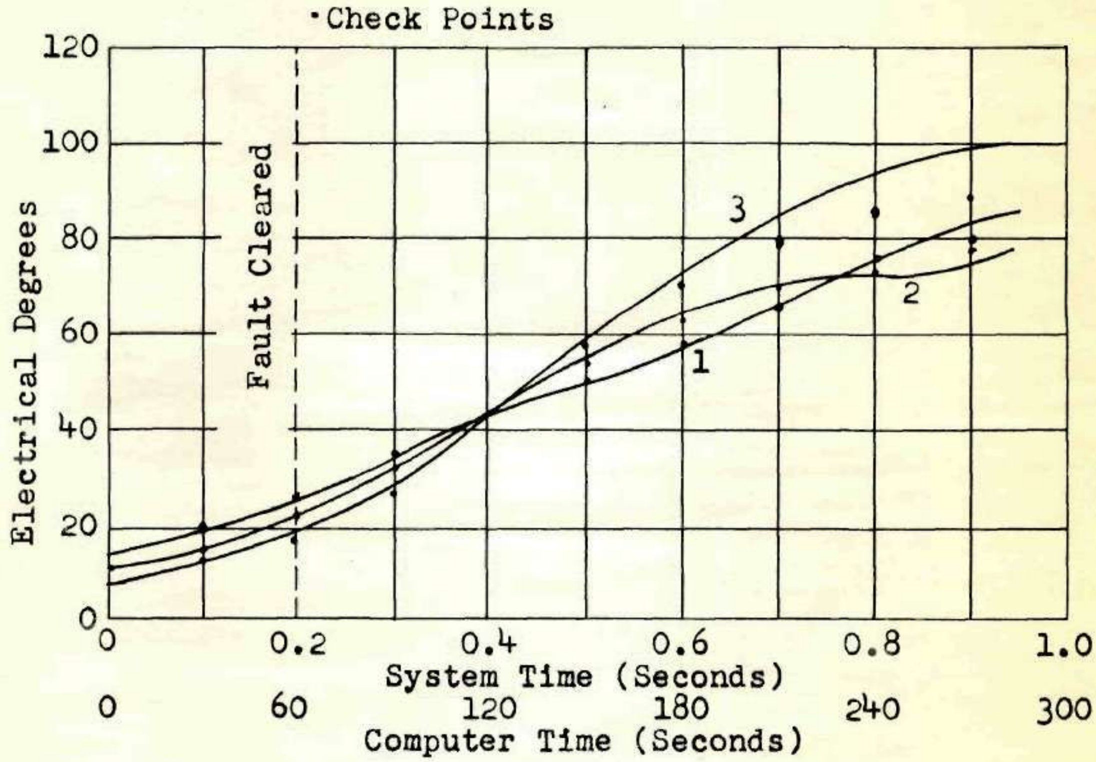


Figure 10

Three Machine Test System

Constructional problems in the electrical circuits were mostly unwanted feedback or pickup. All of the shielded cable shown in the schematic diagram is necessary to the proper operation of the unit. Mechanically, the hardest problem was fitting the servo motor, tachometer, and synchro transformer into the allotted space in the network calculator. The gear box, of course, requires precision machining to keep the backlash to a minimum. None of these problems are basic detriments of the idea of such a computer, but are rather basic to servomechanisms and computers in general.

The problems involving the basic ideas turned out to be mainly operating problems. Of primary concern is the time required to return the system to steady state conditions. As mentioned previously, this tendency was ameliorated by addition of a signal from the tachometer that would damp out the oscillations. There should be a control on this signal so that its level could be adjusted by trial to an optimum value for the particular machine represented. In addition, a stroboscopic light should be installed lighting the moving elements of the computers so that the departure from reference speed could be easily noted. This would greatly assist the initial balancing operation.

The addition of the stroboscopic light would make it easier to run a test on a system that did not include an infinite bus. In such a case the system would have to be set up originally with one machine considered to be infinite.

After steady state conditions are gained, then the computer on that machine would have to be started and P_1 adjusted, with the position servo turned off, so that the disc turns at exactly reference speed as indicated by the stroboscopic unit. The position servo can then be turned on and the system is then ready for the stability test.

The control on P_1 should be calibrated approximately in per unit power output so that an initial balance could be attained without consulting the master instruments. This approximation should be as accurate as is compatible with the economics involved.

The servo motor assembly as constructed in this project was equipped with limit switches. It would be preferable to design the unit so that a mechanical stop would be sufficient and yet not injure the gear box or motor by leaving it energized. This depends in part on the motor used but in any case could be accomplished by a friction clutch between the servo motor and the phase shifter that would slip under overload conditions.

A commercial model should include either a means of mechanically disconnecting the servo from the phase shifter or a hand control on the error signal so that manual operation could be easily accomplished when necessary.

An inherent limitation to the use of these units in a completely general stability study is that the study cannot be stopped at a particular instant of time and resumed later after voltage and power flow conditions have been read. This difficulty can be overcome in a sense because the system generator angles can be duplicated after a study has been completed.

Further refinements which would eliminate the need for the assumptions discussed in Chapter I should be studied before a commercial model of the computer is built. Damping torques could be taken into account by properly adjusting the tachometer feedback to the watthour meter element. This adjustment would require knowledge of the damping torque coefficient on the actual machine and would be a cut-and-try adjustment on the computer as is herein described. A calibrated damping system might be feasible.

To simulate voltage regulator action the network calculator would have to be equipped with servomechanism controls on the existing voltage regulator. In order to match the response of the actual regulator, the servo could be designed with adjustable time constants and "dead band". Simulation of governor action would require a progressive change in P_1. The controls necessary to duplicate such a change could be added at additional cost.

Saliency effects are usually calculated using a rather complex mathematical representation of the machine. Since such a representation cannot be reduced to a simple realizable network on the calculator, the computer necessary to reproduce these effects must be fundamentally different from the one used in this investigation.

None of the problems encountered are insurmountable, but merely show the direction in which further development should proceed.

CHAPTER IV

CONCLUSIONS

The computers, as designed and built, show conclusively that an economical computer and servo system can be applied to a multi-machine transient stability problem on existing network calculator installations. The accuracy is acceptable in the majority of studies and refinements in design should decrease the operating error.

At the present time transient stability studies take up only a small percentage of calculator time. Thus, the units would ordinarily be used to merely hold preset generator outputs. With small additional cost the voltage could also be regulated and steady state problems could be balanced much faster. It is expected that addition of these units would greatly increase the number of transient studies run.

Estimated cost of the units per generator is \$500. Addition of voltage regulators would cost approximately \$200. These figures include the price of the power supply for that one unit. Because one central power supply could serve all the units in a multi-machine installation, the over-all cost for each computer and servomechanism would be slightly less than the figures quoted. The addition of analogs to simulate the voltage regulator and governor actions would increase these costs by an amount which would depend on the final design of the analogs.

Additional operating controls and functions, as follows, should be added to a commercial installation.

1. Stroboscopic lights on the computer rotating elements.
2. Adjustable damping control on the rotating elements.
3. Calibrated P_I settings.
4. Potentiometers on the phase shifters so that their phase angles could be recorded directly.
5. Provision for manual control of the phase shifters.

There are also a number of modifications in design constants that should be made. Of primary concern among these are changes in the negative resistance and the position servomechanism. The negative resistance as is given in Appendix I has much more feedback than is necessary if the proper operating and maintenance programs are carried out. The servomechanism would function better if the motor used had a higher maximum torque, thus necessitating a smaller gear ratio to the phase shifter shaft. Proper choice of motor size should eliminate the necessity of a tachometer feedback in the servo loop.

These suggestions will lead to a better coordinated design with attendant benefits to ease of operation and accuracy.

APPENDIX I

DESIGN OF THE NEGATIVE RESISTANCE AMPLIFIER

The amplifier needed to complete the negative resistance, as shown in Chapter II, is a 52.8 watt amplifier working into 3.3 ohms, with a stabilized gain of 11.0. The gain should be adjustable over a small range so that small variations between phase shifters could be balanced out.

In order to supply the power to the small load resistance an output transformer must be used. It would also be desirable to transformer-couple the input so that the d-c ground would be separate from the a-c input and output. It was found that inexpensive transformers produced too much phase shift to accomodate a high negative feedback without producing oscillations. Final design used a common ground on the input and a transformer coupled output. This requires that the negative resistance on each phase shifter must operate with a common ground if all are to be supplied from the same d-c source.

The power stage of the amplifier was chosen to be 4-6L6's in push-pull-parallel, AB_1, with fixed bias, supplying a plate-to-plate load of 3300 ohms. This stage will then deliver approximately 53 watts with a gain of 0.8.

If the over-all open-loop gain will vary ± 15 per cent due to tube and component variation, then the median gain must be 440 in order to give less than a $\pm$ 2 per cent change in the stabilized gain of 11.0 that is desired. Two stages of amplification were used. The input is one half of a 6SL7 with a gain of 50. A phase inverter 6SN7 with a gain of 13 supplies the push pull power stage. This gives an open-loop gain of 520 (54.3db) when the amplifier supplies a 3.3 ohm load.

Unfortunately, the open-loop gain for use in determining whether or not the feedback circuit will cause oscillations is 73 db. This is due to the fact that for internal disturbances the output transformer is apparently unloaded except for the feedback network. Thus, the phase shift and gain ($A_v\beta$) characteristics that must be shaped properly are found from measurements on the transformer when it is loaded only by the feedback network. Because an inexpensive output transformer was used in combination with high negative feedback, an electrostatic shield was necessary between the primary and secondary windings. Results of the open circuit test combined with the nominal gains of the two other stages and the feedback network are plotted in Fig. 11.

The low frequency end requires an attenuation of 40 db with less than 90° phase shift in approximately one decade of frequency change; the upper end requires 45 db with less than 140° in nearly two decades. In order to accomplish these attenuations it was decided to use a twin-T feedback network around the first stage, as described in Valley and Wallman[19].

The design of the twin-T network is straightforward

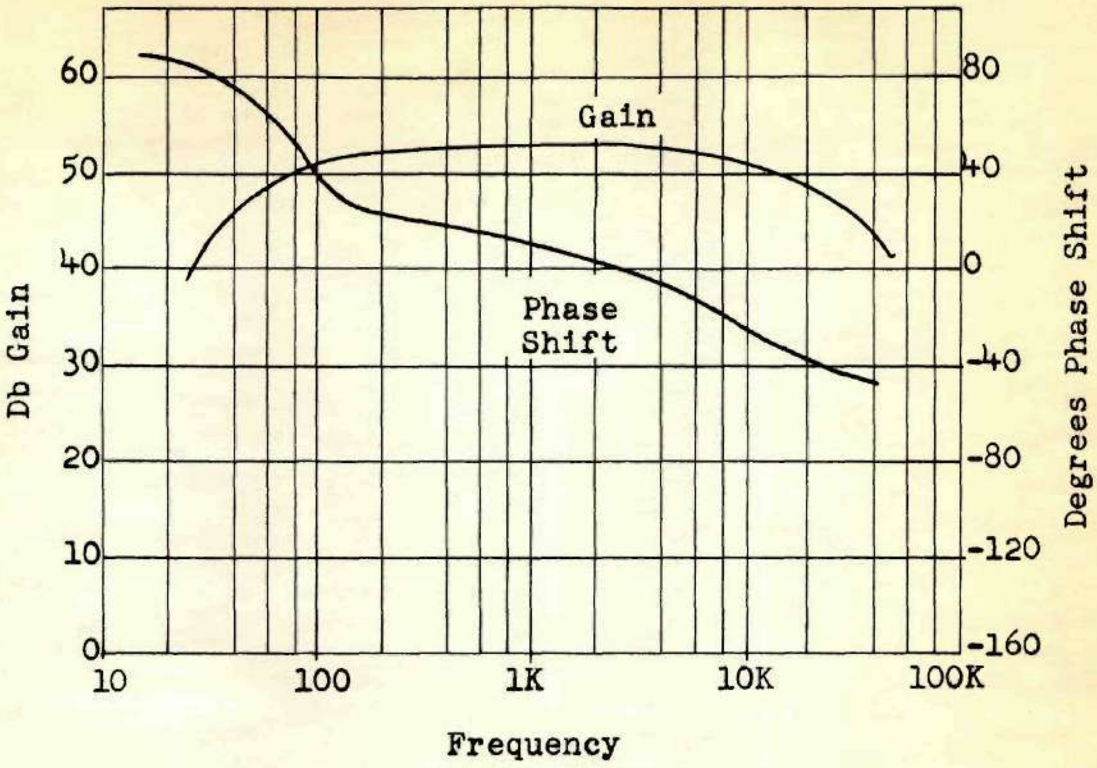


Figure 11

Open Loop Gain and Phase Shift

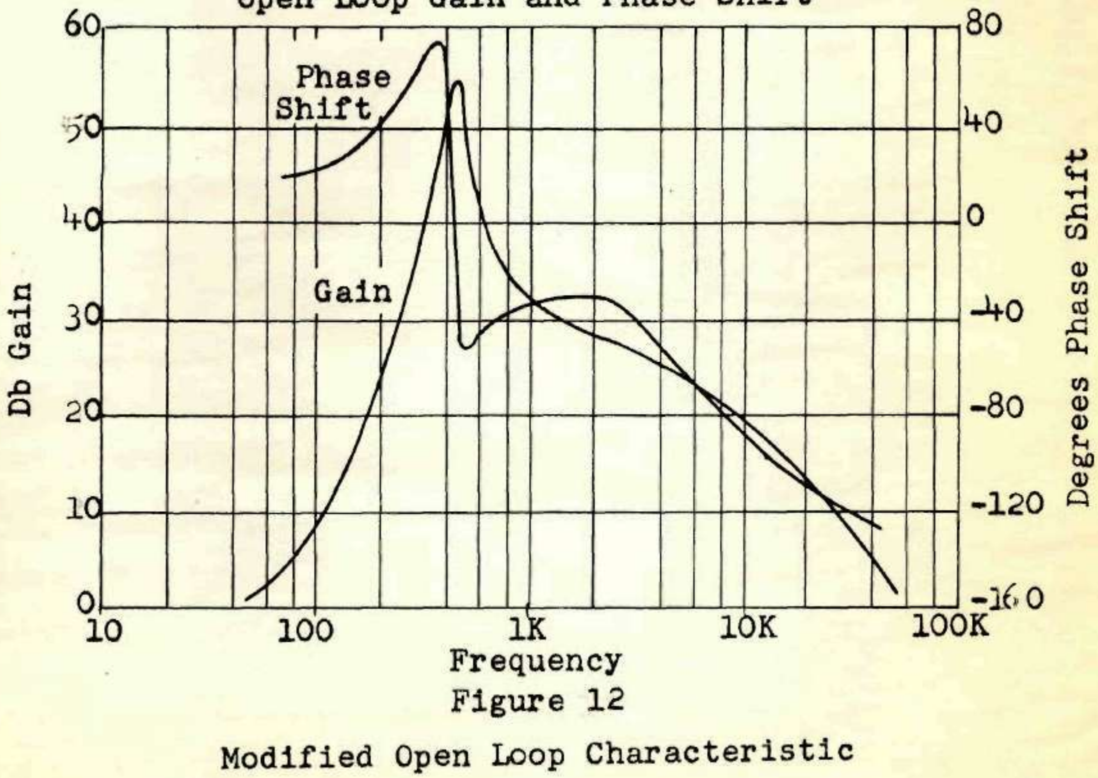


Figure 12

Modified Open Loop Characteristic

with a rejection frequency of 440 c.p.s. Because the twin-T network must operate unloaded, it is fed into the grid of the tube. The signal is applied to the cathode. The first stage acts as a grounded grid amplifier at the rejection frequency of the network. Rheostats are used in the network to allow it to be tuned to 440 c.p.s. The addition of two break points on the log-frequency plot at 63 c.p.s. and 5000 c.p.s. by means of the coupling networks completes the requirements of non-oscillating operation.

The open-loop phase shift and gain characteristics of the amplifier circuit, as shown in Fig. 3, are plotted in Fig. 12 with β taken as 0.1. The 200 ohm rheostat shown in the feedback path in Fig. 3 is to allow β to be adjusted over a narrow range and thus change the value of the negative resistance.

As explained by Ginzton[12], this series type of negative resistance will oscillate if the impedance in a series closed loop with it is less than its own value. This affords an easy method for adjusting the negative resistance value to exactly cancel the phase shifter impedance. The negative resistance is connected across the terminals of the phase shifter and is set for its highest value. The value of the negative resistance is gradually decreased until the oscillations just cease. A check can then be made under load conditions to certify that the voltage regulation and no-load to full-load phase shift are zero.

It should be noted that this negative resistance is probably overdesigned for the most economical performance. The amount of negative feedback used will give less than two per cent change in the negative resistance and yet it would take a ten per cent change in the negative resistance to give a one per cent regulation. The value of negative resistance could be checked periodically at not very much expense; thus, the fifteen per cent change in tubes could be compensated.

For a commercial model whose resistance value will be checked periodically only enough feedback should be used to give a two per cent change in resistance from no-load to full-load. Most of this change will be due to change in amplification of the power stage.

APPENDIX II

DESIGN OF THE COMPUTER AND SUPPLY

As outlined in Chapter II the computer must produce an output phase angle given by Eq. (20); however, the equation of motion of the watthour meter disc is given in Eq. (21). In order to match these two equations a term must be added to Eq. (21) that will cancel the velocity damping and the friction. This term is derived from the tachometer on the servo and can be combined with the reference power, P_1.

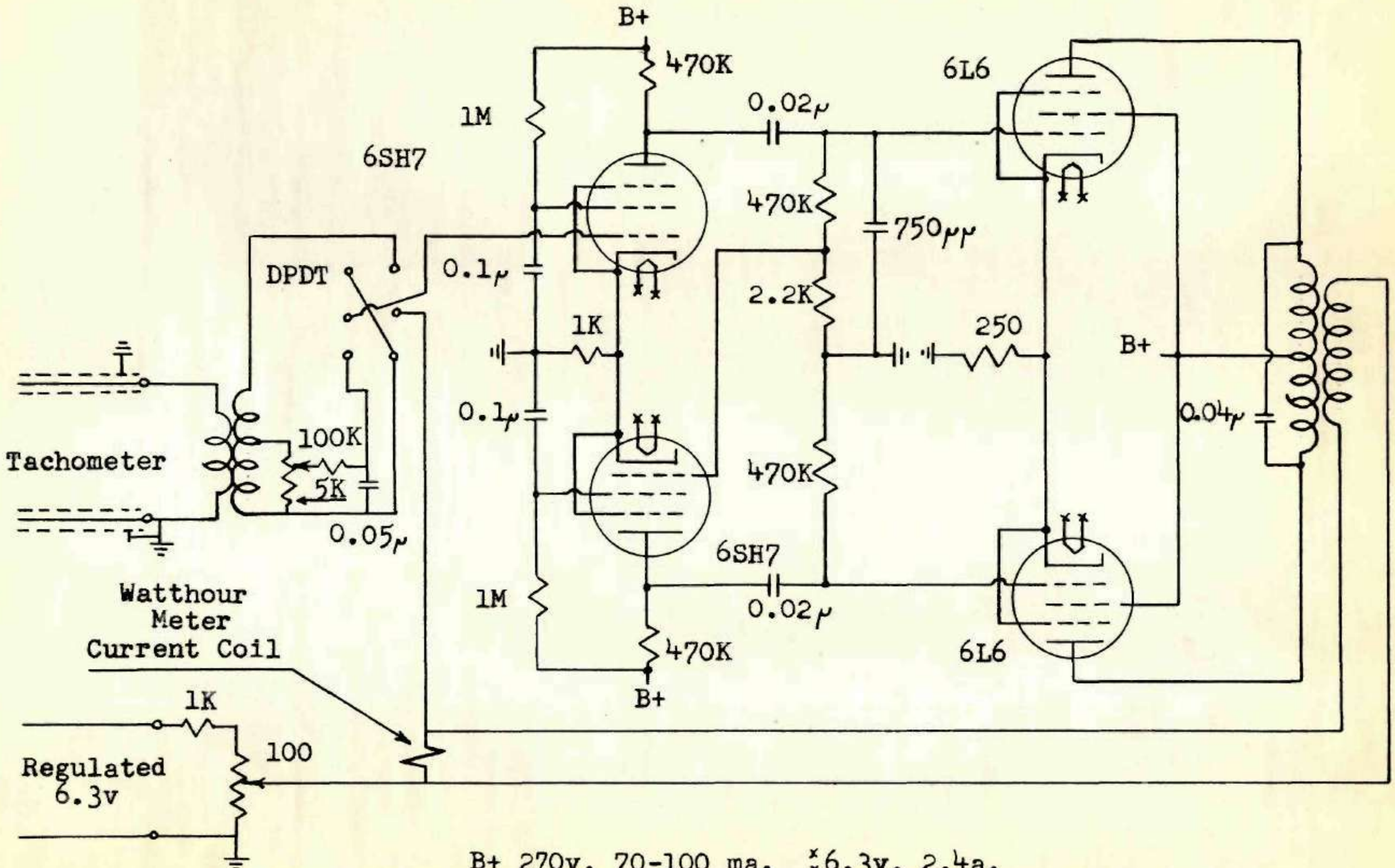
The torque due to the reference power, K_p P_1, is derived from one set of electromagnets; the term K_p P_2 is from another set. Two electromagnets and the segmented disc of a General Electric type V, multi-element meter, were used as the primary elements. The disc was mounted on a shaft extension that had been added to a Pioneer Instrument AY-43DW synchro transmitter. The standard shaft on the transmitter was then available to mount the additional inertia necessary to duplicate Eq. (20). The value of this inertia is found from Eq. (27).

The power output of the calculator generator was fed directly to one electromagnet in order to create the torque K_p P_2. The lag adjustment on the electromagnet was found to be sufficient to properly lag the element on the 440 cycle per second board frequency. This adjustment was obtained by adjusting for constant speed with constant power at various power factors.

The torque to represent P_I and the viscous damping-friction compensation were combined on the other electromagnet. The potential coil of this element was supplied with a constant voltage from a constant voltage transformer. The current coil was supplied by an amplifier whose input consisted of the sum of an adjustable regulated voltage and the output of a potentiometer connected to the tachometer output. Provision was made to reverse the tachometer output in order to increase the viscous damping.

The amplifier to supply the current coil of the element is shown in Fig. 13. The phase shift network on the output of the tachometer potentiometer is to shift this voltage to be in phase with the reference voltage. One hundred per cent negative feedback is used to stabilize the gain of the amplifier. Because the tachometer is part of the measurement process, its excitation winding is supplied from a regulated source.

The tachometer potentiometer is adjusted by test to compensate for the viscous damping present when both electromagnets of the computer are excited with approximately rated voltage. This adjustment is made by a cut-and-try procedure. The watthour meter is supplied with sufficient power to the No. 1 coil to make the disc rotate at the reference speed, 60 r.p.m. The potentiometer, which regulates the tachometer



B+ 270v, 70-100 ma. ˣₓ6.3v, 2.4a.

Figure 13
Circuit Diagram of Amplifier to Supply Watthour Meter Element Number 1

input to the amplifier, is adjusted such that a mechanically forced change in speed will perpetuate itself and neither increase nor decrease. In practice, a very slight decrease is acceptable and is preferable to any increase in the change. During this test, the input power to element No. 2 must be zero and the servomechanism must be operative.

The 100 ohm potentiometer is adjusted at the beginning of a test to produce the desired steady state power output on the board generator. This sets P_2 equal to per unit P_o and the steady state P_1 is equal to per unit P_I, plus the necessary friction compensation, plus an additional amount to give a reference speed of 60 r.p.m. This reference speed was attained by means of a single-phase four-pole, 60 cycle per second capacitor-run type of induction motor. Four slots were milled in the rotor to give a strong saliency effect. The reluctance torque that resulted was sufficient to drive three synchro differentials through the gear ratio of 30:1.

In order to evaluate the magnitude of the inertia to add to the rotor of the computer the constants of Eq. (27) must be determined. N_G was designed to be 86.7 and K_p was found to vary slightly between the units with an average value of 6.87×10^{-7}. The initial inertia of the moving element was found to be negligible for the ordinary study. Thus, the additional inertia to be added to the disc is approximately

$$J = 4.54 \times 10^{-5} \frac{\mu^2 M}{\text{Base Kva}} \qquad (28)$$

Three computers of this basic design were constructed, adjusted, and tested as part of an electric power system.

APPENDIX III

DESIGN OF THE SERVOMECHANISM

The design of the servomechanism is built around readily available war surplus equipment in order to utilize the economies of this source of supply. The units and the necessary constants for this particular application are given in Table 1.

The gear box that links the phase shifter, motor, tachometer and control transformer is dependent on several factors. The first factor is the maximum speed of the phase shifter in a typical problem. This speed can be determined from the natural frequency of oscillation of the system and an assumption of the maximum rotor angle excursion on a particular machine. Rudenberg[20] shows that a typical power system may have a natural frequency of one to two cycles per second. Assuming that the maximum excursion is 120° then the maximum speed will be $\frac{251}{\mu}$ r.p.m., where μ is the time expansion used in the study.

The maximum satisfactory speed of operation[21] of the synchro control transformer has been found in practice to be about 300 r.p.m. Thus, the gearing from control transformer to phase shifter was set at about 100:1. Due to gear ratios and mechanical distance available between the shafts, a value

Table 1
Components Used in the Servomechanism

Part	Manufacturer	Model No.	Design Data
Motor	Western Electric	KS 9154	60 cycle, 2 phase, drag cup fixed winding excited with 12 volts, 60 cycles. $J_m = 1.685 \times 10^{-9}$ slug-ft.^{2} $K_t = 1 \times 10^{-3}$ ft.-lb./volts on control windings $D_m = 1.1 \times 10^{-5}$ ft.-lb./radian/sec.
Tachometer	Pioneer Instruments	10047-2-A	400 cycle, 2 phase, drag cup motor. Will operate as an a.c. tachometer. Fixed winding 6.3 volts, 60 cycles: $V_T = 1.72 \times 10^{-4}$ volts/radian/second. $J_T = 0.652 \times 10^{-9}$ slug-feet squared.
Synchro Transmitter	Pioneer Instruments	AY-43DW	400 cycles, 27 volts. Will operate on 6.3 volts, 60 cycles and supply the following synchro differential, and two control transformers.
Synchro Differential	General Electric	2J1H1	400 cycles, 57.3 to 57.3 volts
Synchro Control Transformer	General Railway Signal Co.	2J1G1	400 cycles, 57.3 to 57.3 volts. When supplied by transmitter and differential as above $V_e = 0.62$ volts/radian of error. $J_{ct} = 6.98 \times 10^{-9}$ slug-feet squared.
Phase Shifter	Existing Equipment		$J_{p.s.} = 2.26 \times 10^{-2}$ slug-feet squared.

of 86.7:1 was used.

The phase shifter has a static torque of 0.1 ft.lbs. when delivering a load of approximately 400 watts. The motor has a speed vs. torque characteristic as shown in Fig. 14. The figure shows that there must be an appreciable gear ratio between the motor and phase shifter in order to allow room for control above static load torque. The gear ratio was again chosen with regard to physical dimensions and was chosen as 2100:1. This ratio is excessive. A better design would use a motor with more power supplied to the fixed winding, thus giving a larger maximum torque and decreasing the necessary gear ratio. The amplification produced by the large gear ratio could more easily be introduced in the electronic amplifier.

The tachometer was geared to the motor with a gear ratio of 10:15 yielding a ratio between tachometer and phase shifter of 3150:1.

The design constants of Table 1 when referred to the phase shifter shaft will have the values shown in Table 2. The open-loop transfer function of the servo will then be

$$G(s) = \frac{\frac{V_e K_t}{D_m}}{s\left(\frac{J_s}{D_m} s + 1\right)} = \frac{2.32}{s(0.000763\ s + 1)} \qquad (29)$$

This response is plotted in Fig. 15 and analyzed by the method set forth by Brown and Campbell[22]. This analysis shows that

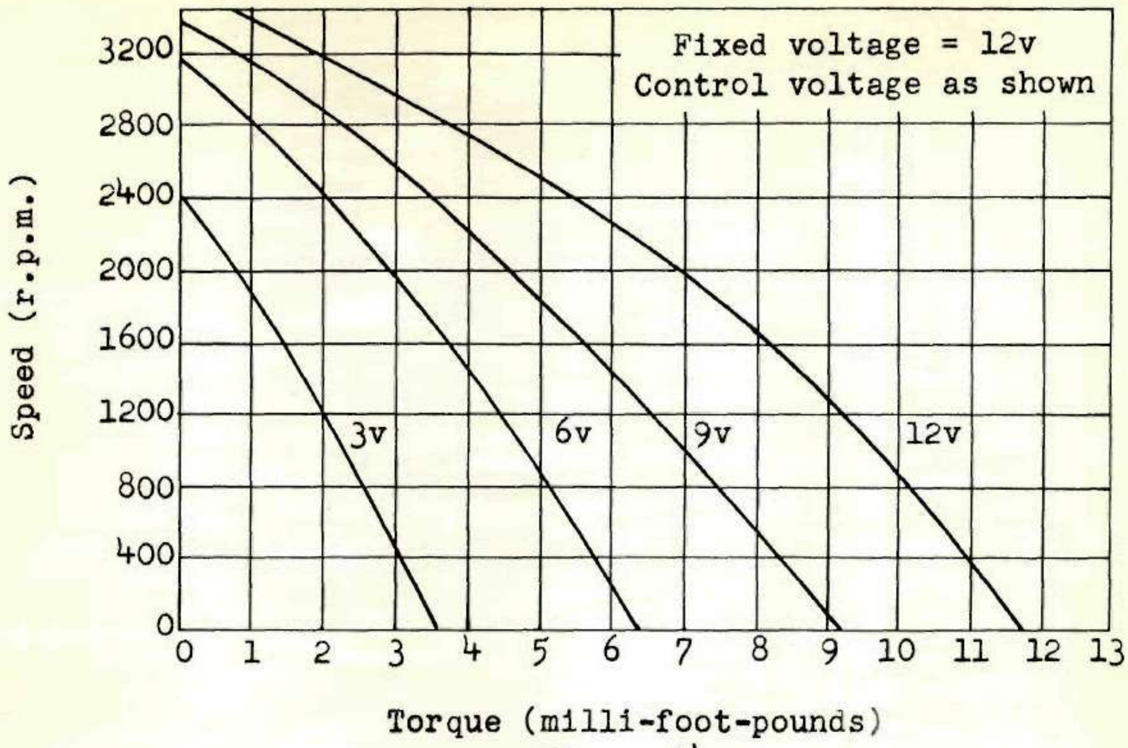


Figure 14

Speed *vs* Torque Characteristics of Two Phase Motor

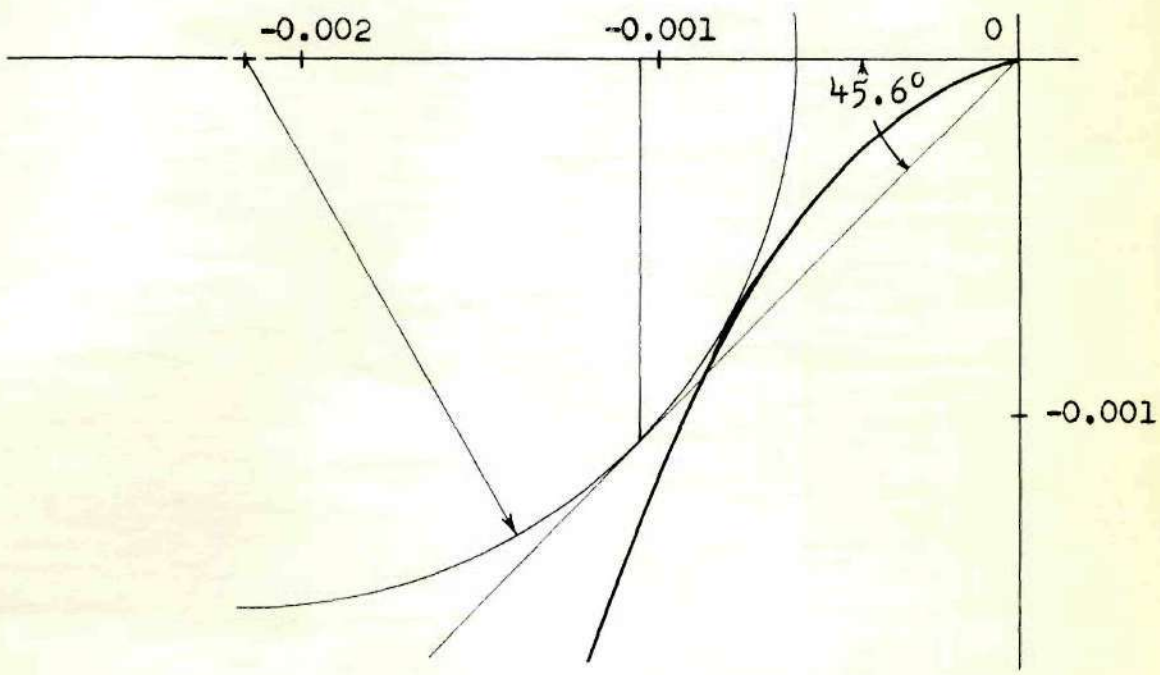


Figure 15

Open Loop Characteristic of the Servomechanism

Table 2
Design Constants Referred to Phase Shifter Shaft

J_s (inertia of servomechanism) = 0.037 slug-ft^2.

K_t = 2.1 ft. lb. per volt on control winding.

D_m = 48.5 ft. lb. per radian per second.

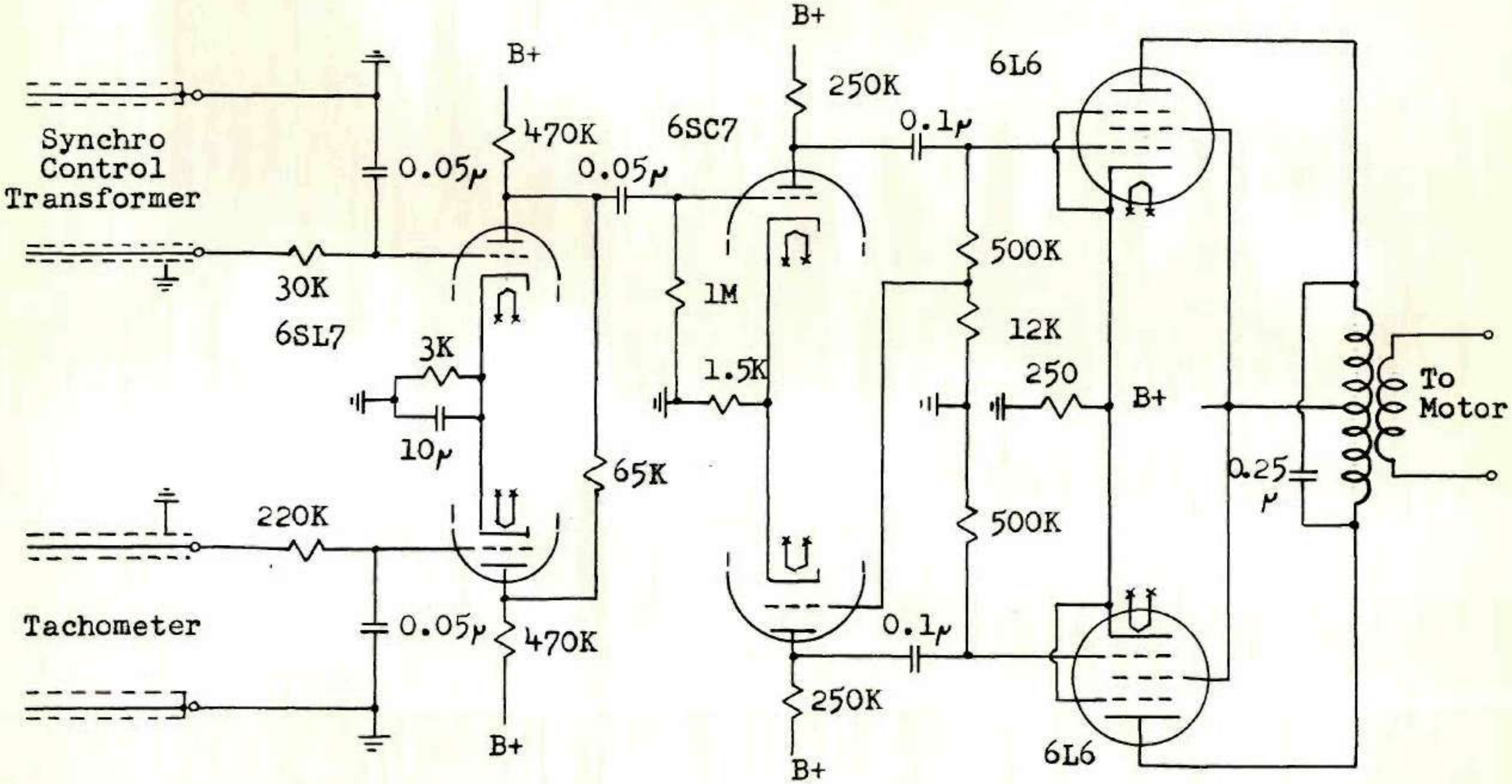
V_T = 0.542 volts per radian per second.

V_e = 53.7 volts per radian of error.

an additional gain of 930 can be used with a resultant value of M_m of 1.4. Approximately this value of gain was used but, due to the backlash in the gear train, a tachometer feedback had to be used to stabilize the system in the manner noted by Tustin[23]. The tachometer feedback loop to the motor terminal was found by trial to need a gain of approximately 200. The servo motor amplifier is shown in Fig. 16.

One of the problems associated with the use of these parts in the servomechanism was fitting them physically into the allotted space. An exploded view of the existing and new equipment is shown in Fig. 17. A more detailed diagram of the gear box is illustrated in Fig. 18.

A test was conducted with the synchro generator stopped and the reference speed of 60 r.p.m. applied to the synchro differential. The steady state error signal from the control transformer was 0.075 volts. From Table 2, V_e equals 53.7 volts per radian of error at the phase shifter. Thus, the error is 0.08 degrees at this constant velocity input.



B+ 270v, 130-160 ma. ×6.3v, 2.4a.

Figure 16
Servomechanism Motor Amplifier

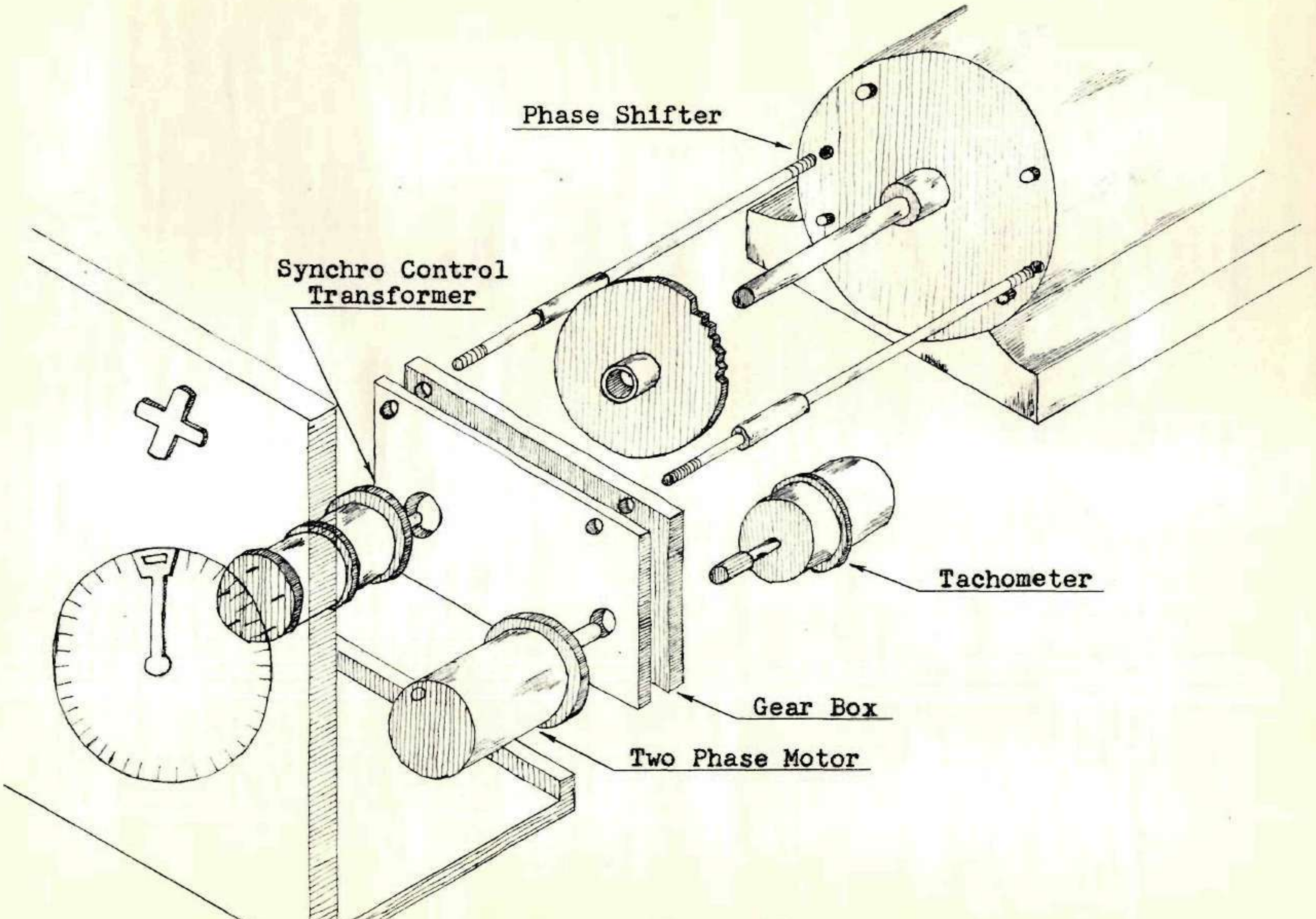


Figure 17
Exploded View of Servomechanism and Phase Shifter

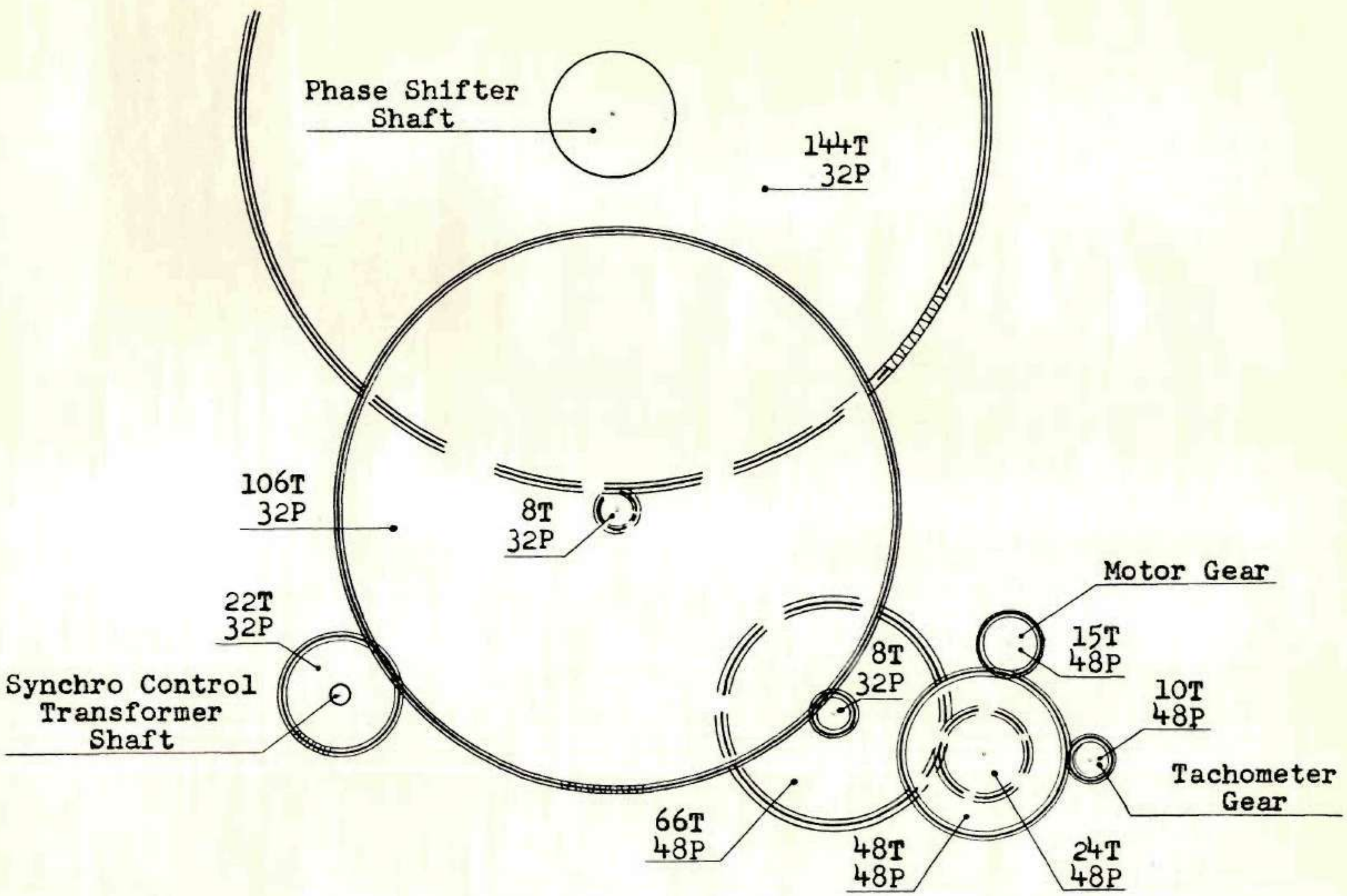


Figure 18
Servomechanism Gear Box

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VITA

The author was born in San Angelo, Texas on October 17, 1926. He lived in San Angelo until he graduated from High School in 1943. The summer of 1943 until June 1946 was spent at the A and M College of Texas with one summer off to work for the West Texas Utilities Company.

After graduating with a B.S. in Electrical Engineering, he worked on the student engineering program at Westinghouse in Pittsburgh. In March 1947, he returned to A and M where he helped install and operate the network calculator and also taught part-time.

He completed his work for a M.S. in August 1951 and registered as a professional engineer in Texas. In 1952 he was awarded a National Science Foundation Fellowship to study for the PhD degree at the Georgia Institute of Technology. The Georgia Tech Alumni Association awarded him a scholarship in 1953 so that his work could be completed sooner. At the present time he is an assistant professor at the A and M College of Texas.